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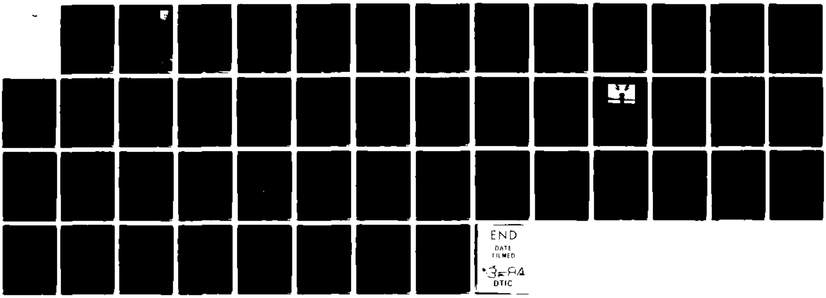

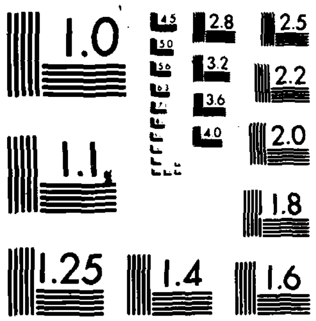

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AFWAL-TR-83-3116

LIGHTNING DATA ANALYSIS

Lightning Location and Protection, Inc.
1001 South Euclid Avenue
Tucson, Arizona 85719

December, 1983

FINAL TECHNICAL REPORT FOR PERIOD JULY 1981 through JULY 1983

FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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A detailed lightning channel reconstruction has been performed for a lightning event recorded as a WC-130 aircraft instrumented for electric and magnetic field measurements was flown in South Florida in the vicinity of a network of ground-based stations that provided wideband electric fields at ground level and data that could be used to determine the location of lightning and VHF sources. Maximem rates of change of airborne electric fields from the last few stepped leader pulses and from the fast field transitions of return strokes are shown to be an order of magnitude smaller than those reported for measurements at ground level

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) over salt water. Two sets of calculations are presented for lightning return stroke electric and magnetic fields at flight altitudes, one set assuming an initial peak current which propagates up the channel unattenuated and the second set assuming a current peak which decreases exponentially with height with a decay length of 1.5 km. A recommendation is given for a lightning return stroke test standard for average first and subsequent return strokes and for a comparison of lightning and EMP.

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LIGHTNING DATA ANALYSIS

SECTION I. INTRODUCTION

This Final Report on Contract F33615-81-C-3410 is divided into three parts: Part 1 (SECTION II) discusses our analyses of correlated airborne and ground-based electromagnetic data obtained during the AFWAL/FIESL lightning characterization program in South Florida; Part 2 (SECTION III) is concerned with the calculations of lightning return-stroke electric and magnetic fields at flight altitudes; and Part 3 (SECTION IV) includes the specification of a lightning test standard and a discussion of the validity of deriving lightning currents from electric and magnetic fields measured remote from the lightning. This part also discusses some calculations of electric field frequency spectra and a comparison of lightning and an NEMP produced by an exoatmospheric burst.

SECTION II. CORRELATED AIRBORNE AND GROUND-BASED LIGHTNING ELECTROMAGNETIC DATA

During 1979, 1980, and 1981 the AFWAL/FIESL directed a program designed to characterize airborne lightning electric and magnetic fields (see "Airborne Lightning Characterization", AFWAL-TR-83-3013, January 1983, by P. L. Rustan, B. P. Kuhlman, A. Serrano, J. Reaser, and M. Risley). A WC-130 aircraft, instrumented for electric and magnetic field measurements, was flown in South Florida in the vicinity of a network of ground-based stations that provided wide-band electric fields at ground level and data that could be used to determine the location of lightning VHF sources. A thorough analysis of the voluminous data obtained will take many years. We, in conjunction with AFWAL personnel, have completed a survey analysis of ten lightning events from the South Florida study and a detailed analysis of one event that occurred at 17:09:40 EDT on July 16, 1981. Appendix A contains a scientific paper that describes the results of our analysis of the 17:09:40 event. This flash is typical of most of the lightning events in that the results obtained and new questions raised are similar to those for other events.

For the 17:09:40 event, a two-stroke flash with separate channels to ground, lightning channel reconstructions were possible for both channels to ground via the VHF time-of-arrival system. Electric and magnetic fields were recorded on the WC-130 and electric fields were recorded at the ground. The following conclusions can be drawn from the detailed analysis of the 17:09:40 flash and survey analysis of other events: Maximum rates-of-change of airborne electric fields from the last few stepped leader pulses and from the fast field transitions of return strokes are about 3 V/m μs normalized to 100 km. These values are an order of magnitude smaller than those reported by Weidman and Krider (1980) and Weidman (1982) for leader and return stroke pulses measured at ground level over salt water. Figure 1 shows a histogram of maximum $^{dE}/dt$ values measured at ground level over salt water and normalized to 100 km for the fast field transitions of return strokes. The mean is 33 V/m μs. It is crucial to understand why the airborne electric field rates-of-change are so slow. One possible explanation that needs further examination is that since the stepped leader and return stroke fields are generated near the ground, the electromagnetic wave may be coupled to or

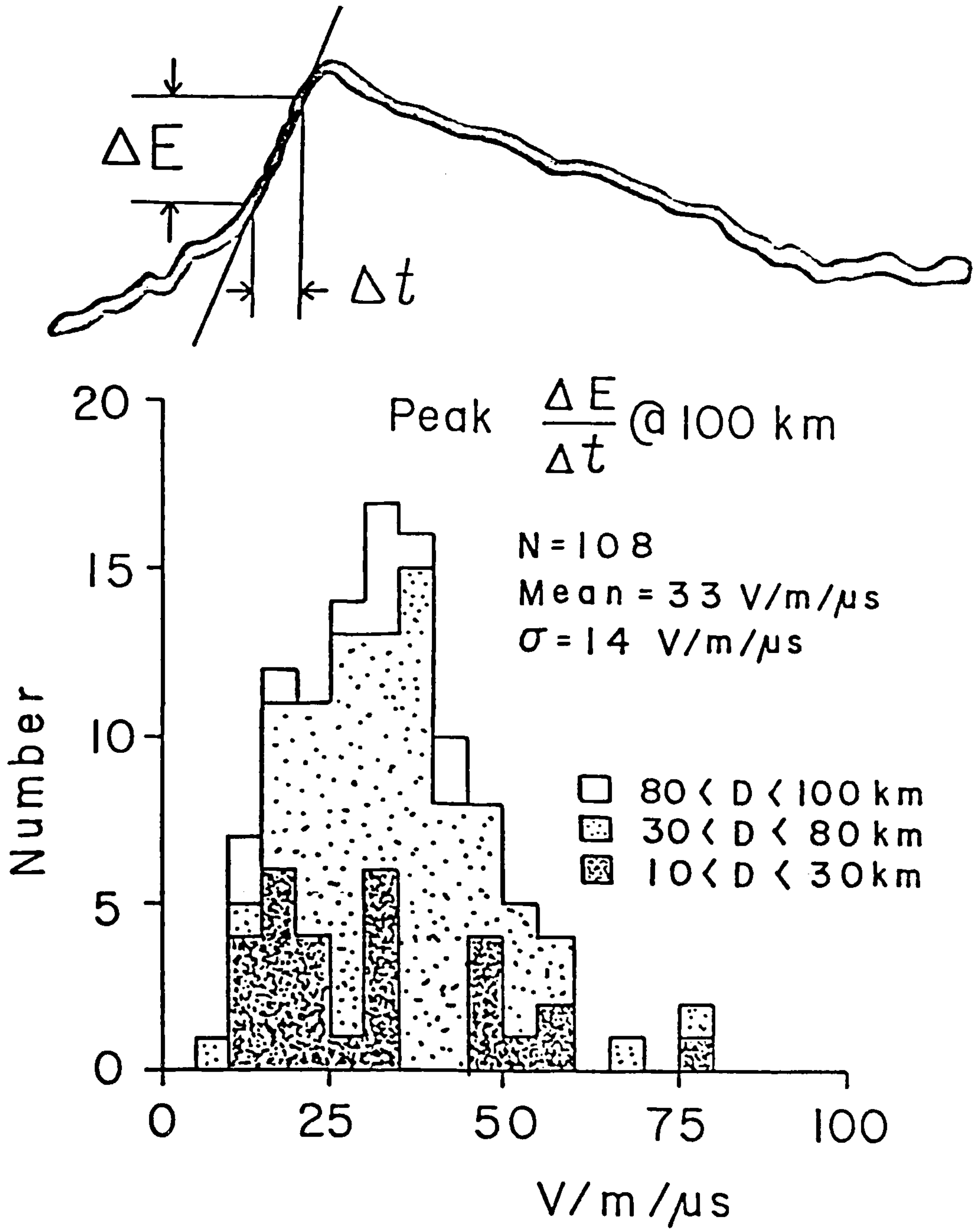

Figure 1. A Histogram of the Measured Maximum ΔE/Δt Values for Return Strokes Normalized to a Range of 100 km (from Weidman, 1982).

reflected from the non-perfectly-conducting earth and thereby produce a degradation of the airborne risetime. A theoretical analysis is possible. Additionally, the fields at the aircraft altitude or above should be examined to see if there are faster rates-of-change that are characteristic of pulses produced far above ground. A search of the records for these kinds of data is outside the scope of the present study.

Electric-field risetimes measured on the aft upper fuselage of the WC-130 are always faster, up to 0.5 μs faster, than those measured on the forward upper fuselage. Further, the field amplitudes on the aft upper fuselage are a factor of 3 to 4 smaller than on the forward upper fuselage. The model study by Electro Magnetic Applications, Inc. (EMA) of the electromagnetic response of the WC-130 aircraft to the electromagnetic signals originating at the known locations of the stepped leaders and return strokes of the 17:09:40 event show the risetimes of the two sensors to be identical. Moreover, each antenna response is essentially the incident field times a scale factor. A possible explanation for the observed difference in the two sensors is that on the actual aircraft there was a thin-wire antenna above the aft upper fuselage antenna which both could have shielded it and could have caused resonances that affected the measured risetime. It was not reported until very recently that there was such a thin-wire antenna on the WC-130, so the antenna was not modeled in the EMA study. Future work should include modeling of the exact configuration of the aircraft including all wire antennas. The measured fields on the aircraft show a pronounced resonance at about 3.7 MHz which is not produced by the model illumination of the WC-130 with a spherical electromagnetic field. The model calculations show a relatively small resonance at about that frequency. In order to understand better the generation of resonances, the model calculations should be expanded to include field components in the direction of propagation which may be more efficient excitors of resonances. The effects of angle of incidents of the incoming electromagnetic wave on the aircraft response should also be studied.

SECTION III AIRBORNE ELECTRIC AND MAGNETIC FIELD CALCULATIONS

The results of our calculations of lightning return stroke fields above ground are given in the scientific paper in Appendix B. Two sets of calculations are presented: those for which the initial peak current propagates up the channel unattenuated and those for which the peak decreases exponentially with height with a decay length of 1.5 km. Recent work by Jordan and Uman (1983) has shown that, while the return stroke light decays exponentially with height with about a 1.0 km decay length, the relation between light and current is such that, in all probability, the current decays much more slowly with height than does the light. Thus, the fields to be expected above ground should be between the two cases presented in Appendix B.

The results in Appendix B are primarily concerned with overall field waveshapes and no data are given on risetimes. The risetimes in the air above a perfectly conducting ground are determined by both the risetime of the line-of-sight wave and the delayed risetime of the reflected wave from the ground. For each small channel section that radiates a field the propagation delay is different, and thus the total risetime observed above a perfectly-conducting ground can only be determined by a relatively complex calculation. In view of the fact that the risetimes measured on the WC-130 aircraft are substantially slower than ground-based measurements made over salt water, as noted in the previous section, the calculation of airborne risetimes, even for the case of a perfectly conducting earth, would appear to be desirable.

SECTION IV. LIGHTNING TEST STANDARD

Tables IA and IIA of the scient ic paper in Appendix C give our recommendation for a lightning r urn stroke test standard for average first and subsequent return kes, as well as a comparison of lightning and NEMP. We recommend, as noted in Appendix III, that severe strokes be modeled by scaling the current amplitudes for average strokes up by a factor of 5. We have chosen to use current waveforms derived from remote field measurements rather than those found from direct tower measurement (given in Tables IB and IIB) for the reasons discussed in Appendix C and in the following. The best available direct current measurements, as discussed in Appendix C, come from Berger and Garbagnati and are based on strikes to towers on two mountains near the Swiss-Italian border. In these data, the risetimes of first return strokes are considerably slower than those of subsequent strokes and a peak current derivative, dI/dt, of 1×10^{11} A/s occurs in about 1% of the subsequent strokes. However, in a South African study, as noted in Appendix C, a dI/dt of 1.8×10^{11} A/s was measured for one lightning strike to a tower on relatively flat ground in a small sample of flashes. This case is apparently the largest dI/dt that has been measured directly. Later measurements on the same South African tower (Erikkson, 1982) using a waveform digitizer showed 4 out of 5 subsequent strokes in a six stroke flash (out of a sample of 3 multiple-stroke flashes) had risetimes less than 0.2 μs, the sample time, and the $^{dI}/dt$'s greater than 0.68, 1.3, 1.5, and [illegible] times 10^{11} A/s. Whether currents measured on towers are truly representative of the currents in the lightning channel above ground, or of the currents that would flow through an aircraft above ground, is not known. The shape of the tower current, particularly that [illegible] the first return stroke in a flash, is not consistent with the electric and magnetic fields produced by normal lightning to ground (Weidman and Krider, 1978). Unfortunately, there are no simultaneous measurements of the electromagnetic fields and currents during subsequent strokes in rocket-triggered flashes, and they have used the measurements to compute return stroke velocities using the theory given in Appendix C. Using this method, the French obtained a [illegible] velocity of 1.3 x 10^8 m/s with a standard deviation of 0.34 x [illegible] using magnetic fields, and a mean of 1.7 x 10^8 m/s with a standard deviation of 0.43 x 10^8 m/s using electric fields (Fieux et al., [illegible] Dejebari et al., 1981). These velocity determinations are consistent with the photographic measurements of Idone and Orville ([illegible]) who report a mean of 0.96 x 10^8 m/s for first strokes within 1 km [illegible] ground and a 1.2 x 10^8 m/s for subsequent strokes. Therefore, we regard the French measurements on triggered lightning as providing some support for the theory given in Appendix C. It is interesting to note that the 10-90% risetime of the French current pulse that [illegible] shown as an example is about 0.1 μs and that the peak current is about [illegible] 10 kA (Fieux et al., 1978), yielding a $^{dI}/dt$ of 1 x 10^{11} A/s.

Return stroke currents that are derived from measured fields [illegible] a mean maximum $^{dI}/dt$ of about 1.5 x 10^{11} A/s, and the maximum measured value is about 4 x 10^{11} A/s in about 100 measurements. Therefore, the mean maximum $^{dI}/dt$ derived from fields is equivalent to the [illegible] in the tower data. In the paper in Appendix C, we have assumed that a typical lightning has maximum $^{dI}/dt$ of 1.5×10^{11} A/s and peak current of 35 kA, and that a severe lightning has a maximum $^{dI}/dt$ and peak current that are five times larger than the typical lightning, i.e. 7.5×10^{11} A/s and 175 kA, respectively. These choices for a severe lightning have been criticized because they associate the largest peak current with the greatest $^{dI}/dt$. We shall explore the validity of these choices below.

Figure 1 shows the submicrosecond structure of a typical return stroke radiation field and identifies the portion just prior to the peak that has the largest $^{dE}/dt$. In our model, $^{dE}/dt$ is directly proportional to $^{dI}/dt$ and the constant of proportionality contains the return stroke velocity near ground, as noted in Appendix C. A histogram of measured $^{dE}/dt$ values normalized to 100 km for the fast field transition are plotted in Figure 1 for lightning at a number of distances over salt water (Weidman and Krider, 1980; Weidman, 1982). These measurements were made over salt water, and evidently the propagation distance does not affect the measured values. The mean maximum $^{dE}/dt$ during the fast transition is 33 V/m μs normalized to 100 km, and the mean 10 to 90% field risetime is 90 nsec during the fast transition.

Figure 2 shows the relationship between the maximum $^{dE}/dt$ and the corresponding ΔE during the fast transition. The values of $^{dE}/dt$ and ΔE do appear to be correlated, and this implies that a large current peak will produce a large $^{dI}/dt$ as we have assumed for our severe lightning. On the other hand, only 8 out of 108 points in Figure 2 are above 50 V/m μs, and these have a larger variation in ΔE than the points below 50 V/m μs. Therefore, it might be argued

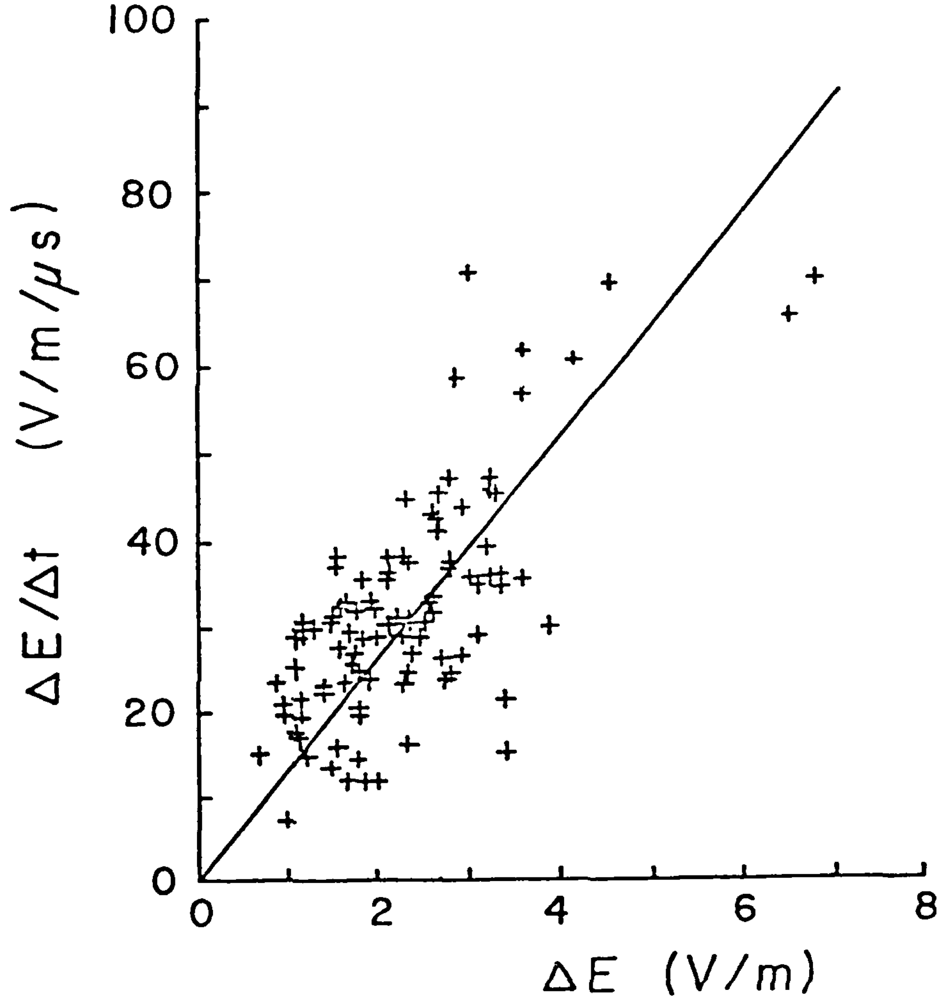

Figure 2. The Correlation Between Return Stroke ΔE/Δt and ΔE Range Normalized to 100 km (from Weidman, 1982).

that there is not enough $^{dE}/dt$ data to draw a firm conclusion about the distribution at high values of $^{dE}/dt$. It has been suggested that the data may be approaching a limit at about 75 V/m μs, but this does not appear to be valid in view of the small number of measurements. It has also been suggested that the data above 50 V/m μs may be produced by a different process than the data below this value, e.g. by two channels radiating simultaneously, but there is still no direct evidence that this suggestion is valid.

Figure 3 summarizes all the available data on the values of the maximum return stroke $^{dI}/dt$. The data for the field-derived $^{dI}/dt$ are plotted assuming a return stroke velocity of 1×10^{8} m/s. The plotted lines show where these data would fall if the velocity were either 1.4×10 or 0.6×10^{8} m/s. It is clear from this figure that the average field-derived $^{dI}/dt$'s correspond to the maximum values of the tower measurements for subsequent strokes and that the tower values for first strokes are significantly lower than those for subsequent strokes.

As noted earlier, the validity of our model relating fields and currents is supported by the French measurements on triggered lightning, and we think this model, which assumes that an upward propagating current pulse is associated with the return stroke wavefront, is the best that is currently available. An alternate model, which assumes that a spatially uniform but time-varying current propagates upward, the so-called Bruce-Golde model, yields a field-derived $^{dI}/dt$ that is within a factor of 2 of that found with our model. Essentially all of the high frequency content of the field is determined by the current rise to peak and the current fall just after peak, so the validity of the return-stroke current model after the

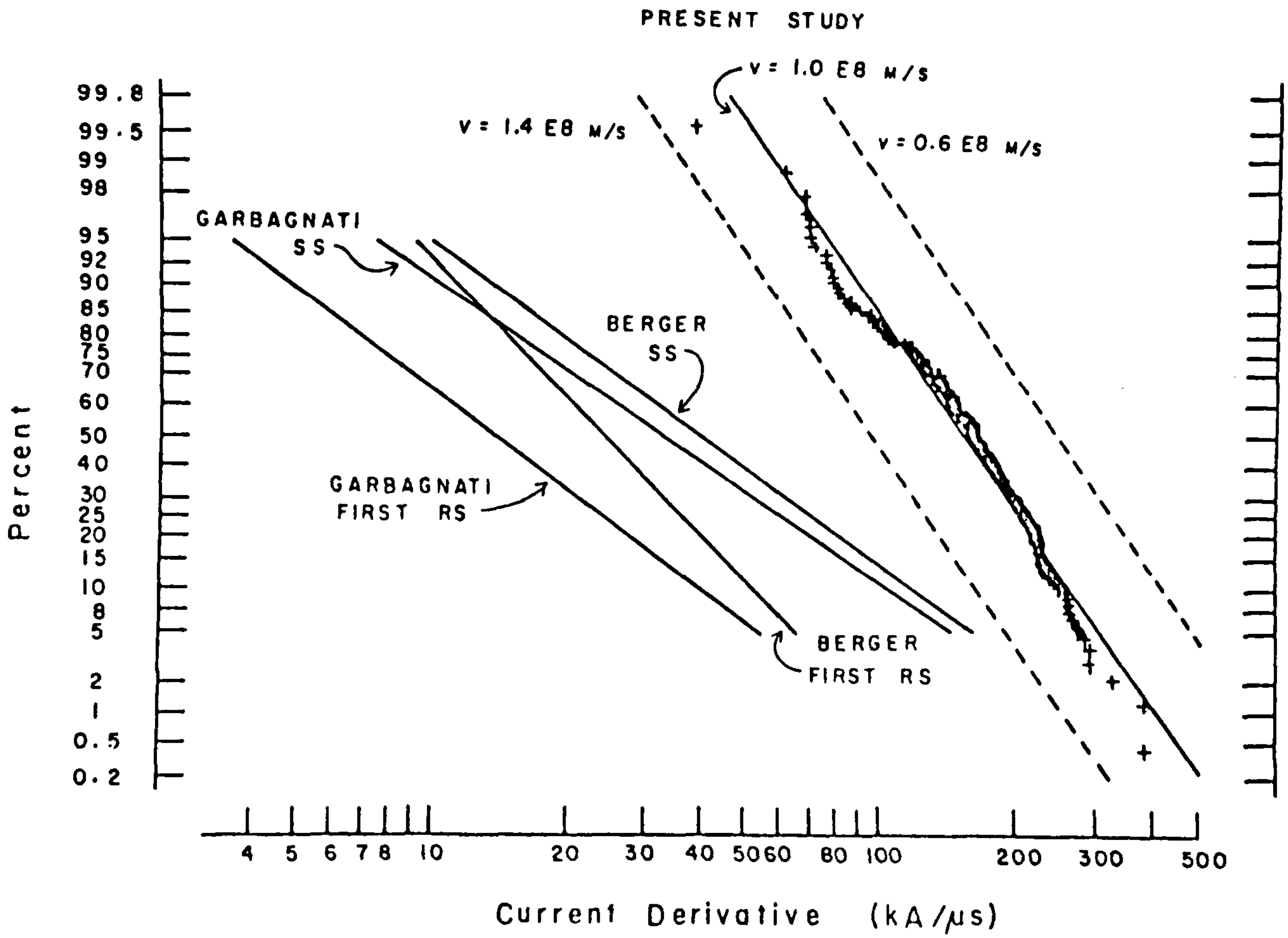

Figure 3. The Distribution of the Maximum $^{dI}/dt$ in Return Strokes Derived from Field Measurements (from Weidman, 1982).

peak is of secondary importance.

It has also been suggested (Uman et al., 1973; Weidman and Krider, 1978) that the initial first stroke field may be produced by currents propagating both upward and downward from the junction between the upward and downward leaders. This effect would lower our field-derived $^{dI}/dt$ by a factor of 2; but such an effect should not occur in subsequent strokes and these are observed to have about the same $^{dE}/dt$ and hence $^{dI}/dt$ as first strokes.

As an extension of the calculations in Appendix C, Figure 4 shows electric field spectra for an average first stroke at distances between 50 m and 10 km. The dashed lines in Figure 4 show the spectra of just the radiation field term so the contribution of the electrostatic and induction fields can be evaluated.

An aircraft in flight probably will not encounter the return strokes current characteristic of ground level considered above; but, on the other hand, the maximum $^{dE}/dt$ values in cloud pulses and leader steps and the associated amplitude spectra above 10^{6} Hz are very similar to those of return strokes (Weidman et al., 1981). Although we do not yet have a model for these processes in which we are confident, the available measurements imply that the maximum current derivatives in these processes are comparable to return strokes. Therefore, we expect that the hazards from the high frequency components of cloud-discharges may well be similar to return strokes near the ground.

Since the actual lightning channel is tortuous, it might be expected that the frequency spectra shown in Figure 4 might be affected by that tortuosity. We argue now that this is not the case

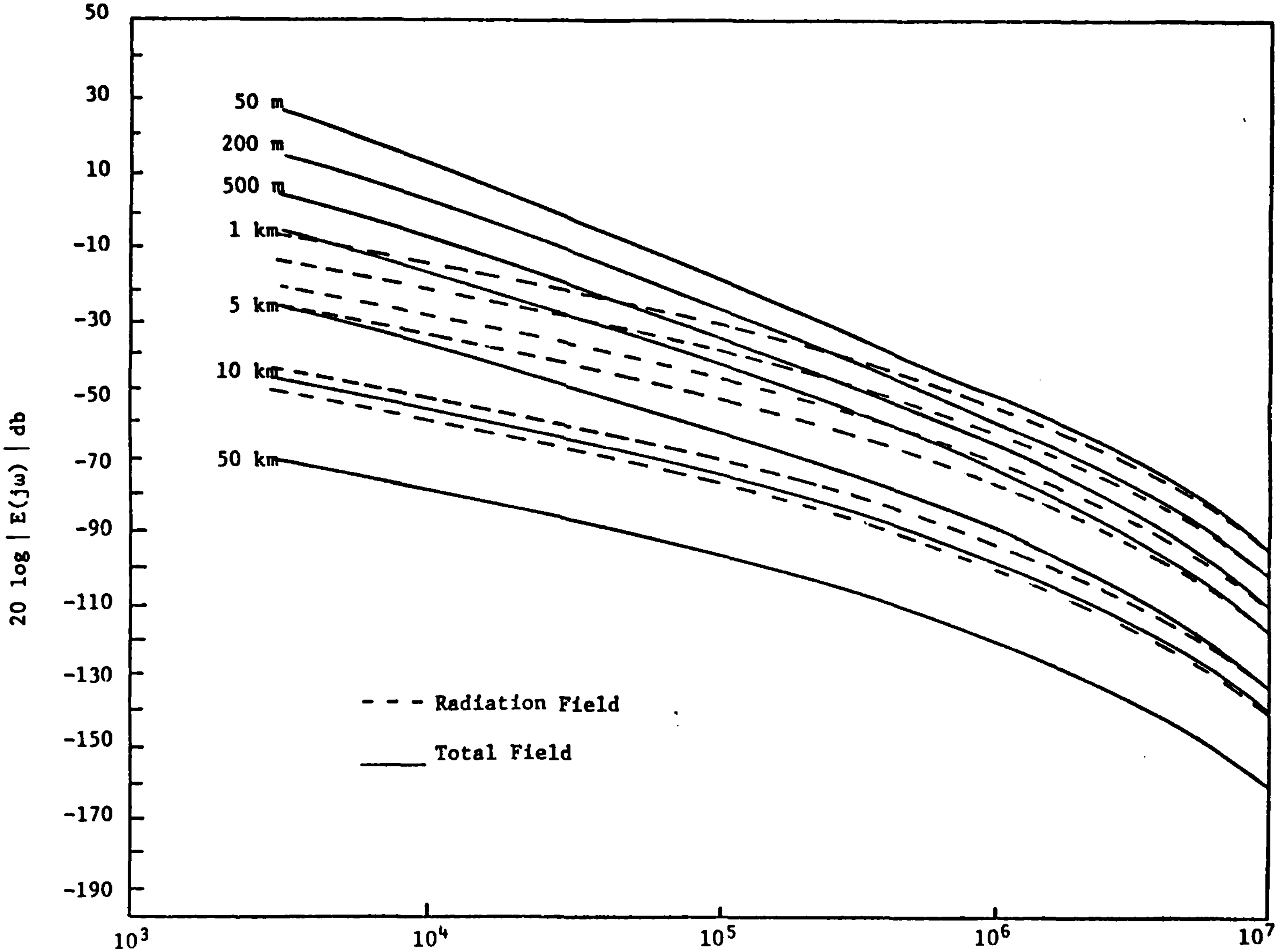

Figure 4. Electric Field Amplitude Spectra for an Average First Stroke vs. Range. The Spectra of just the Radiation Field are Shown as Dashed Curves.

at close range where the large field magnitudes could adversely affect an aircraft. Levine and Meneghini (1978a) have used a simple current model to calculate the fields which are radiated by a tortuous channel and have shown that the tortuosity increases the "jaggedness" of a time-domain waveform and increases the spectral amplitude above 10^5 Hz by about 20 db. We have repeated their calculations for both distant and close (50 m) fields for a first stroke that has the current parameters given in Appendix C, Table 1A. The channel tortuosity is that given in Figure 2 of Levine and Meneghini (1978b). The results are shown in Figure 5, and it is clear that tortuosity does not appreciably alter the spectrum of the electrostatic or induction components which dominate the fields at close ranges. The change in the radiation field spectrum with tortuosity is an increase of about 10 db above 10^5 Hz. These calculations are critically dependent on the channel current waveform and the assumed tortuosity. On the other hand, the time-domain waveforms for the simulated tortuosity are much more "jagged" that the experimental data, which for subsequent strokes are actually quite smooth, so the effects of tortuosity may not be nearly as large as these calculations would indicate. In fact, most of the frequency content above 10^6 Hz in the measured time-domain fields from first and subsequent strokes is produced within 1 μsec or so of the peak field; and this implies that most high frequencies are radiated at a time when the stroke is within a few hundred meters of ground and prior to the time when tortuosity can play a significant role. Why subsequent stroke field waveforms are smooth when photographed channels appear to have considerable tortuosity is not clear. Currently, there are studies under way at the University of Arizona to measure tortuosity and

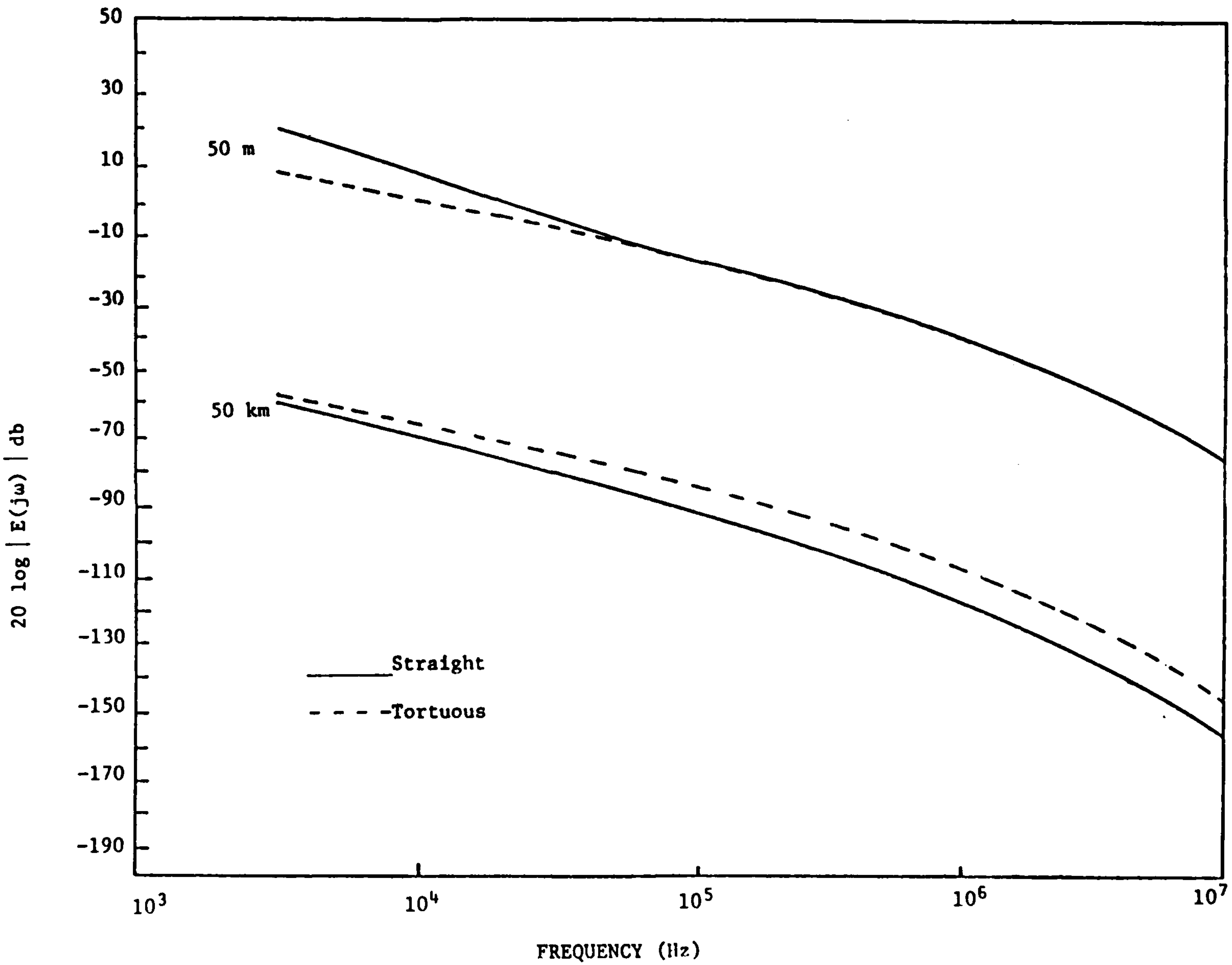

Figure 5. Electric Field Amplitude Spectra for Straight and Tortuous First Return Strokes at 50 m and 50 km.

branching in real channels, and in the future these will be coupled with calculations of fields by the University of Florida. We hope that these future studies will resolve this apparent contradiction.

APPENDIX 1

Airborne and Ground-Based Lightning Electric and Magnetic Fields and VHF Source Locations for a Two-Stroke Ground Flash

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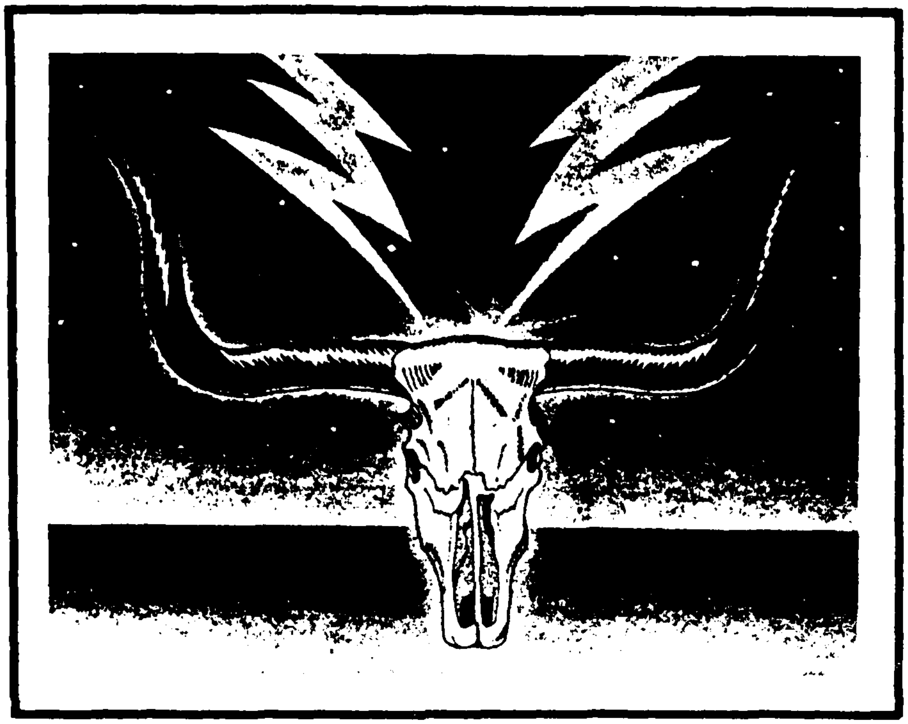

8th INTERNATIONAL AEROSPACE and GROUND CONFERENCE on LIGHTNING and STATIC ELECTRICITY

LIGHTNING TECHNOLOGY ROUNDUP

June 21-23, 1983

Fort Worth, Texas, U.S.A.

AIRBORNE AND GROUND-BASED LIGHTNING
ELECTRIC AND MAGNETIC FIELDS AND VHF SOURCE
LOCATIONS FOR A TWO-STROKE GROUND FLASH

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ABSTRACT

We have reduced and analyzed the data from a two-stroke lightning flash to ground which occurred in South Florida on July 16, 1981, within a network of four ground stations instrumented for VHF measurements, about 15 km from a ground station instrumented for wide-band electric field measurements, and within 10 km of a WC-130 aircraft operating at 5.2 km and instrumented for wide-band electric and magentic field measurements. The four-station ground-based VHF measurements allow a reconstruction of the geometry of the flash, which was composed of two separate channels to ground. Electric field system bandwidth for the ground measurement was from 0.02 Hz to about 2 MHz; electric and magnetic field system bandwidths on the aircraft extended to 20 MHz. Ground-based and airborne measurements of fields are presented and shown to be consistent with one another.

DURING 1979, 1980, AND 1981 THE AIR FORCE Wright Aeronautical Laboratories directed a program designed to characterize airborne lightning electric and magnetic fields. A WC-130 aircraft instrumented for electric and magnetic field measurements was flown in South Florida in the vicinity of a network of ground-based stations which provided electric field at ground level and data from which the location of lightning VHF sources could be determined. Extensive data were obtained. These will take many years to analyze fully. In this paper we briefly describe the instrumentation used during the 1981 measurement season and illustrate the potential of the data base by presenting an analysis of data from one two-stroke lightning flash to ground which occurred at 17:09:40 EDT on July 16, 1981.

AIRBORNE MEASUREMENT SYSTEMS

The WC-130 aircraft is about 30 m from nose to tail and about 41 m in wingspan. Aircraft resonances are expected at half and integer multiples of 9.9 and 7.4 MHz. The airborne instrumentation had an upper frequency response limit of about 20 MHz so that some of these resonance effects could be observed. Three basic types of sensors, described in Baum et al. (1)*, were used: (a) plates to measure the component of the electric field intensity perpendicular to aircraft surfaces, (b) loops to measure the magnetic field intensity parallel to aircraft surfaces, and (c) loops to measure current densities flowing in aircraft surfaces by sensing the magnetic field associated with those current densities. The latter two sensors have essentially similar principles of operation. A total of eleven sensors were used on the WC-130 in 1981. Electric field was measured on the forward upper fuselage, aft upper fuselage, aft lower fuselage, and left wing tip. Both horizontal components of the magnetic field were measured on the forward upper fuselage. Skin current density was measured on the top and bottom of each wing and on the aft upper fuselage. All measured quantities were continuously recorded on instrumentation tape with an upper frequency response limit of about 2 MHz. In addition, the derivatives of the measured quantities were sampled at 20 ns intervals for time blocks of 160 μs. Such blocks of data, with an effective upper frequency response limit of about 20 MHz, were acquired at a rate of twice a second, the data block being initiated in a pre-trigger mode by an incoming signal exceeding a pre-set threshhold.

GROUND-BASED MEASUREMENT SYSTEMS

Ground-based electric field measurements are essential to proper interpretation of the airborne data since considerable information exists on the characteristics of the fields observed at ground level and the relation of those fields to their sources, whereas such information is not available for airborne fields. The ground-based electric field system was similar to that described in Beasley et al. (2). The fields were recorded on eight channels of an instrumentation tape recorder with a bandwidth in the FM mode of 0.02 Hz to 500 kHz and in the direct mode of 400 Hz to 2 MHz. A variety of gains allowed the measurement of fields between 4 V/m and 40,000 V/m. Fig. 1 shows the overall experimental setup including the location of the trailer that housed the electric field system.

The VHF source location system comprised four VHF stations located about 20 km apart as shown in Fig. 1. The VHF radiation at each station was (a) detected with an omnidirectional antenna, (b) passed through a filter with a center frequency of 63 MHz and a bandwidth of 6 MHz, (c) log amplified, (d) envelope detected, and (e) recorded on a modified version of the RCA VCT 201 Video Cassette Recorder. The system allows VHF locations from the measurement of the difference in the time of arrival of a given pulse at the four stations as explained in Rustan et al. (3) and Proctor (4). The time correlation necessary for this measurement, about 0.1 μs, was accomplished by using WWV for crude time correlation and the vertical and horizontal sync pulses from WINK-TV in Fort Myers (shown in Fig. 1) for fine time correlation. The horizontal sync pulses have a rate of one each 63 μs.

*Numbers in parentheses designate References at end of paper.

DATA

A conceptual sketch of the lightning channels of a two-stroke flash occurring on July 16, 1981 at 17:09:40 EDT is shown in Fig. 1. The sketch is based on the VHF time of occurrence and location of the VHF radiation sources shown in plan view in Fig. 2a and looking north in Fig. 2b. The location and orientation of the WC-130, which was flying at 5.2 km, is also shown in both figures.

Both strokes appeared to originate from about the same region, but the second went to a different ground strike point, about 5 km north-west about 250 ms after the first stroke.

The first VHF radiation sources start about 50 ms before the first return stroke, at an altitude of about 7 km, that is, 2 km above the level of the WC-130, and about 7 km east and 3 km south of it. The source locations then spread up and down about 1 km and east to about 8 km in about 5 ms. During the last 5 ms before the return stroke, the source locations are at an altitude between 4 km and 1 km, from 7 to 10 km east and from 2 to 6 km south of the WC-130. The ground strike point of the first stroke appears to be between 7 and 8 km east and 2 to 3 km south of the WC-130. For about 0.5 ms after the return stroke, VHF sources appear between 3 and 8 km altitude, 7 to 10 km east and 1.5 to 8 km south of the WC-130.

About 200 ms later, VHF sources become active for 0.5 ms between 6 and 3 km altitudes, 5 to 9 km east and 2 to 3 km south of the WC-130. Then, 30 ms later, for about 1 ms, VHF sources appear from 5 km down to 1.5 km altitudes, 4 to 5 km east and 2 to 5 km south of the WC-130. The strike point appears to be about 5 km east of the WC-130.

Figs. 3, 4, and 5 show the vertical electric field at the ground station, the airborne vertical electric field on the aft upper fuselage (AUF in Fig. 1), and the magnetic field in the direction of the fuselage as measured on the forward upper fuselage (FUF on Fig. 1), respectively, for the first stroke in the flash.

The stroke which produced the electric field in Fig. 3 was at a range of 16 km from the ground station and 8 km from the aircraft. The airborne field magnitudes in Figs. 4 and 5 are not corrected for field distortion by the aircraft. The stepped leader pulses which precede the return-stroke transition and the first ten microseconds or so of the return-stroke field are essentially radiation field at these ranges; and the fields on and above the ground are expected to have essentially the same shape (5), as the results in Figs. 3, 4, and 5 confirm. After about 10 μs, the return-stroke electric fields show an electrostatic component which the magnetic field does not possess (5) (6). Additionally, the low-frequency cut off of the system used to obtain the magnetic field shown in the figure decays slightly faster than the actual field.

The first-stroke electric-field intensity measured at the ground station has an initial peak value of 50 V/m, or 8.0 V/m normalized to 100 km, a peak field typical of Florida lightning (7). The comparable field values at the WC-130 are 110 V/m, or a normalized 8.8 V/m, on the forward upper fuselage, and 32 V/m, or a normalized 2.6 V/m, on the aft upper fuselage. The second stroke peak field measured on the ground was 14 V/m, and the stroke was at a range of 14 km, resulting in a normalized field of 2.0 V/m, a relatively small value for Florida return strokes (7). The airborne second stroke fields were comparably small and difficult to make any measurements on other than amplitude. In the first stroke field records the ratios of the stepped-leader pulse heights to the return stroke peak are essentially the same, on average about 0.1, and, as expected, the stepped-leader pulses occur at the same times before the return stroke on all three records, as can be seen in Figs. 3, 4, and 5. The zero-to-peak rise-time of the first return stroke measured at the ground is about 3.0 μs, also consistent with typical values measured in Florida (7), with airborne values of 2.9 μs at the forward upper fuselage and 2.6 μs at the aft upper fuselage. Stepped leader pulses have zero-to-peak rise-times on the ground of about 1 μs and full-widths at the pulse base of about 2 μs. Comparable airborne values are 0.8 μs and 1.1 μs at the forward upper fuselage and 0.3 μs and 1.0 μs at the aft upper fuselage. All measured rise-times are well within system limits. The rise-times on the ground are expected to be longer than in the air because of the effects of groundwave propagation involving a non-perfectly-conducting earth, as discussed in Lin et al. (7), Uman et al. (8), and Weidman and Krider (9). The reason that the rise-times at the aft upper fuselage are faster than those at the forward upper fuselage is not known, but aircraft resonances may contribute to this effect. Wing and fuselage resonances are excited by the airborne horizontal electric field which is the dominant field within about 1 km of a return stroke and is comparable to the vertical field near 10 km (5). The leader pulse rise-times are somewhat slower than the typical values for 10 to 90 percent of 0.1 μs reported in Weidman and Krider (10) for lightning over salt water.

Maximum rates-of change of airborne electric field for both leaders pulses and return strokes were the same, about 40 V/m μs, or 3.2 V/m μs normalized to 100 km. These are to be compared with the normalized mean of 30 V/m μs for return strokes and 21 V/m μs for leader pulses reported in Weidman and Krider (9) (10) for lightning over salt water.

ACKNOWLEDGEMENT

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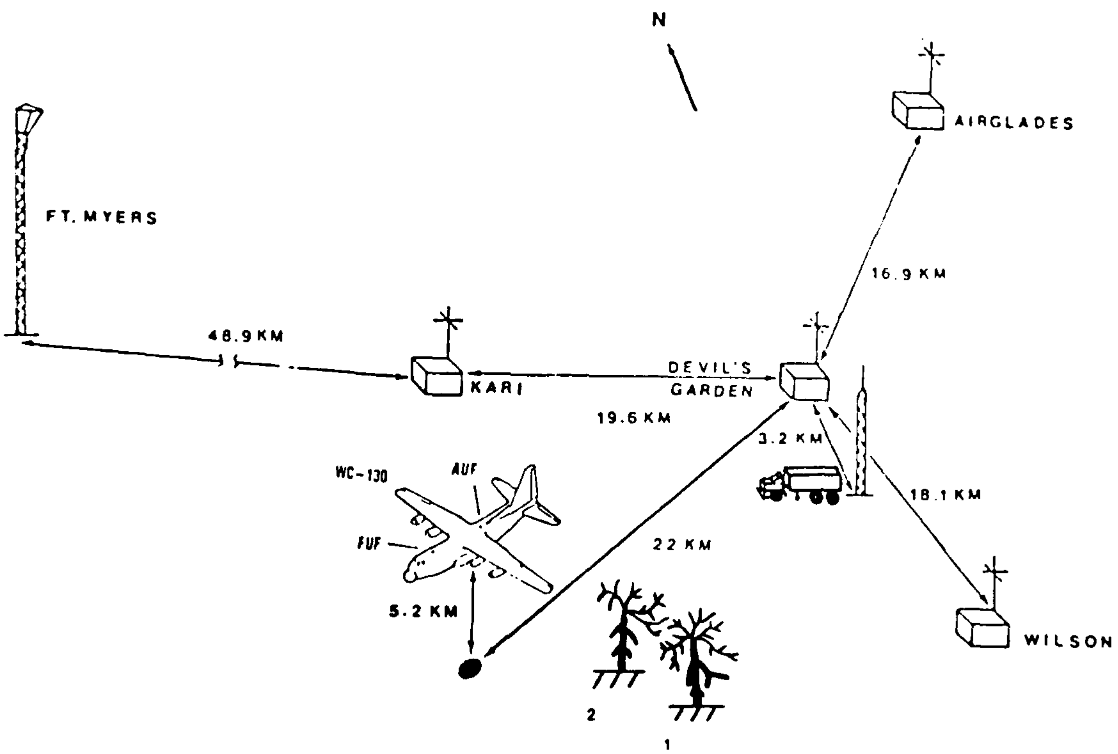


Fig. 1 - The experimental setup including the position of the WC-130 at 17:09:40 EDT on July 19, 1981 and a drawing of the two lightning channels to ground deduced from VHF time-of-arrival measurements

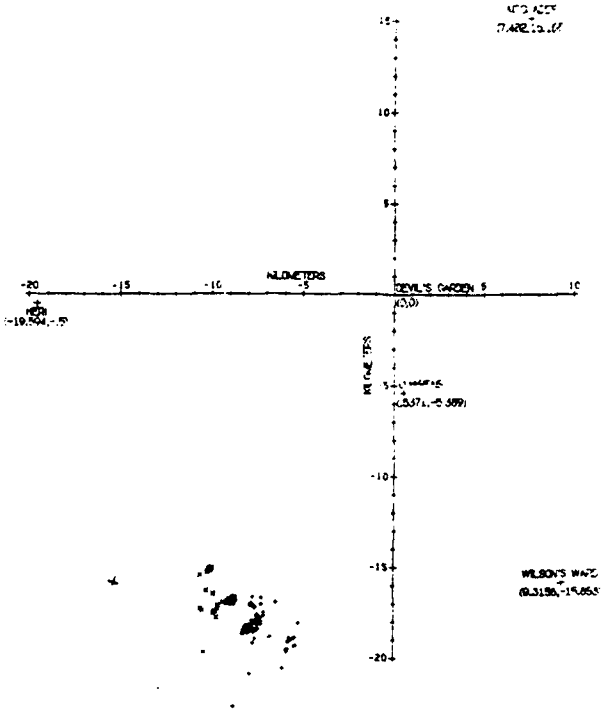
Fig. Captions,Kasemir,Static Discharges..

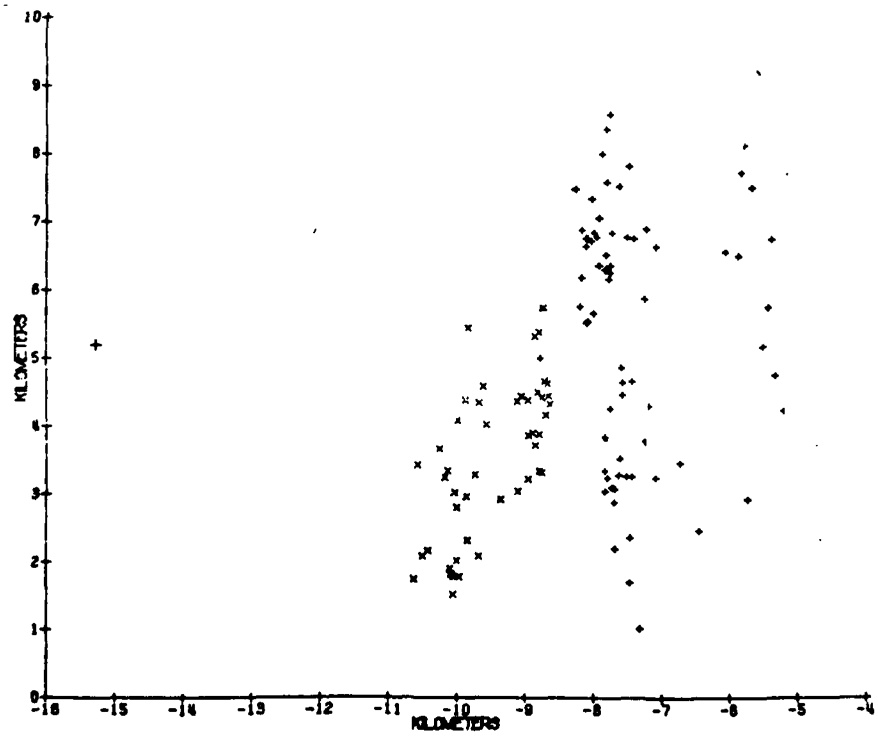
Fig. 1 - Charge distribution on charged leader
a. Stepped leader
b. After returen stroke
c. Cloud discharge advancing upwards
d. Cloud discharge adwandinc downwards

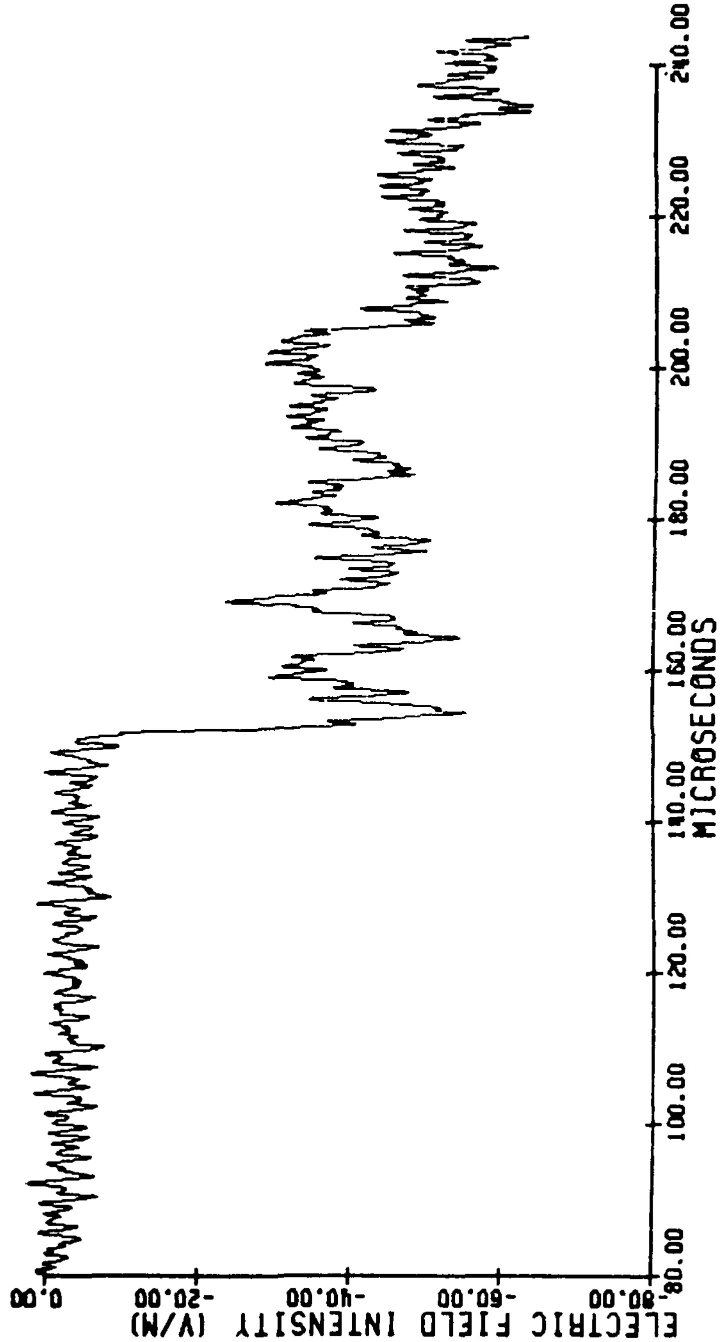
Fig. 2 - Charge distribution on uncharged leader
a. Stepped leader
b. After return stroke
c. Cloud discharge beginning stage
d. Cloud discharge end stage

Fig. 3 - Corona discharge on Orbiter

Fig. 4 - Flash over on Orbiter



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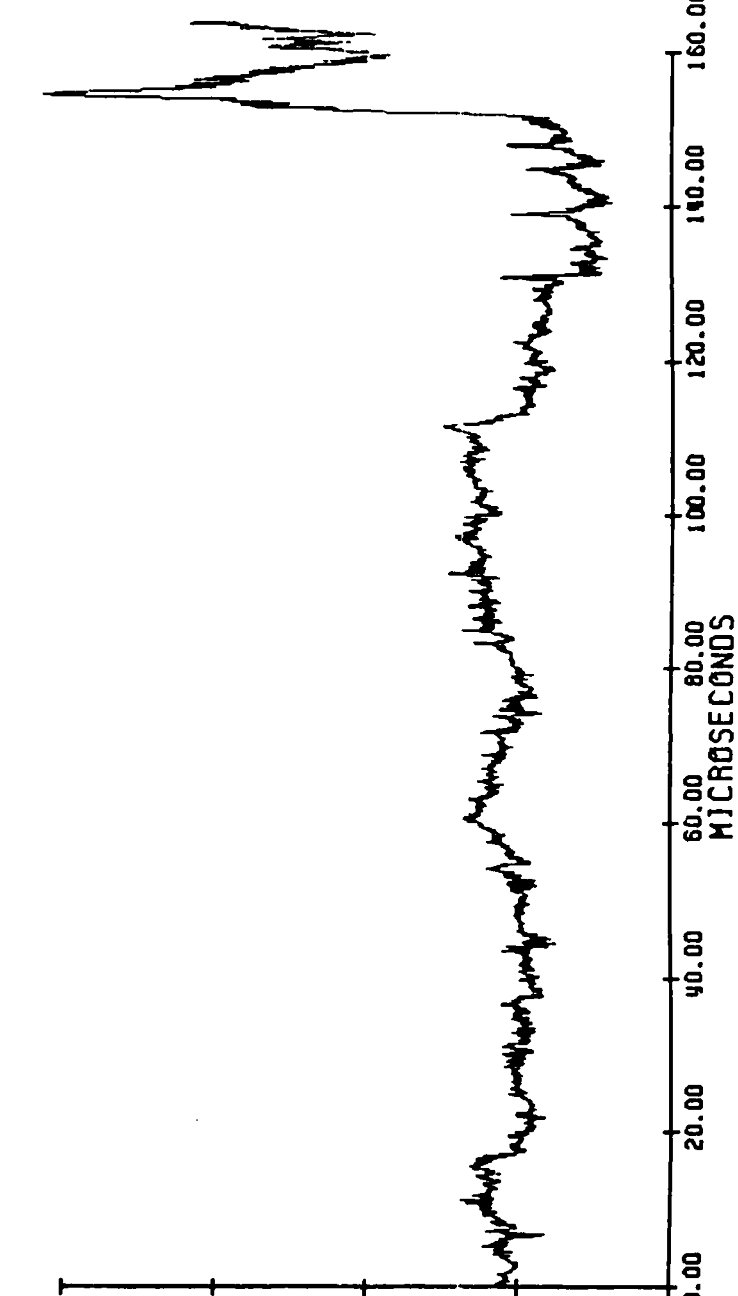
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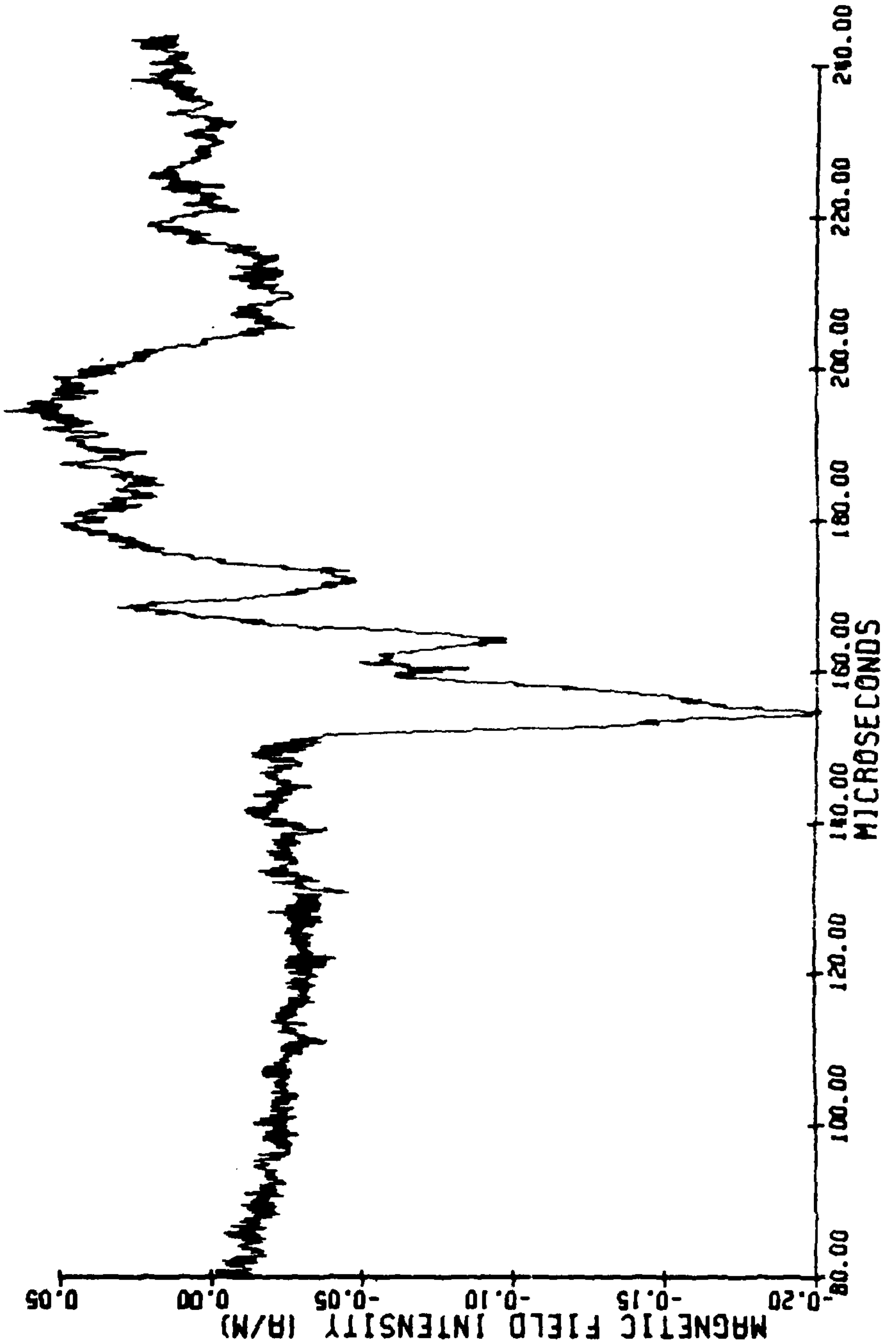
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APPENDIX 2

CALCULATIONS OF LIGHTNING RETURN STROKE
ELECTRIC AND MAGNETIC FIELDS ABOVE GROUND

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Calculations of Lightning Return Stroke Electric and Magnetic Fields Above Ground

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The first detailed calculations of lightning return stroke electric and magnetic fields above ground are presented. Waveforms are given for altitudes from 0 to 10 km and ranges from 20 m to 10 km. These waveforms are computed using the model of Lin et al. (1980) and a modification of that model in which the initial current peak decays with height above ground. Both the original and the modified models result in accurate prediction of measured ground-based fields. Return stroke field measurements above ground close to the stroke, with which the calculations could be compared, have not yet been made. Salient aspects of the calculated fields are discussed, including their use in calibrating airborne field measurements from simultaneous ground and airborne data.

INTRODUCTION

Lin et al. [1980] have recently introduced a lightning return stroke model with which return stroke electric and magnetic fields measured at ground level [*Lin et al.*, 1979] can be reproduced. Here we use that model and a modification of it to compute electric and magnetic fields at altitudes up to 10 km and at ranges from 20 m to 10 km. These calculations provide the first detailed estimates of the return stroke fields that exist above ground and that are encountered by aircraft in flight. The most recent generation of aircraft may be particularly susceptible to lightning electric and magnetic fields because these aircraft are controlled with low-voltage digital electronics and are in part constructed of advanced composite materials which provide a reduced level of electromagnetic shielding [*Corbin*, 1979]. Hence, in the context of aircraft safety, calculations of the magnitude and waveshape of airborne electric and magnetic fields are of considerable practical interest. Furthermore, from a scientific point of view, since airborne electric and magnetic fields are presently being measured [*Pitts et al.*, 1979; *Pitts and Thomas*, 1981; *Baum*, 1980], a comparison of the calculations given in this paper with appropriate experimental data, when they are available, will constitute a test of the return stroke model.

THEORY

The lightning return stroke current is assumed to flow in a thin, straight, vertical channel of height H above a perfectly conducting ground plane, as shown in Figure 1. The electric and magnetic fields at altitude z and range r from a vertical dipole of length dz' at height z' and arbitrary current $i(z', t)$ are

$$d\mathbf{E}(r, \phi, z, t) = \frac{dz'}{4\pi\epsilon_0}\left[\left\{\frac{3r(z-z')}{R^5}\int_0^t i(z', \tau - R/c)\,d\tau + \frac{3r(z-z')}{cR^4}\,i(z', t - R/c) + \frac{r(z-z')}{c^2R^3}\,\frac{\partial i(z', t - R/c)}{\partial t}\right\}\mathbf{a}_r\right.$$

$$\left. + \left\{\frac{2(z-z')^2 - r^2}{R^5}\int_0^t i(z', \tau - R/c)\,d\tau + \frac{2(z-z')^2 - r^2}{cR^4}\,i(z', t - R/c) - \frac{r^2}{c^2R^3}\,\frac{\partial i(z', t - R/c)}{\partial t}\right\}\mathbf{a}_z\right] \quad (1)$$

$$d\mathbf{B}(r, \phi, z, t) = \frac{\mu_0\,dz'}{4\pi}\left\{\frac{r}{R^3}\,i(z', t - R/c) + \frac{r}{cR^2}\,\frac{\partial i(z', t - R/c)}{\partial t}\right\}\mathbf{a}_\phi \quad (2)$$

where (1) and (2) are expressed in cylindrical coordinates, ϵ_0 is the permittivity and μ_0 the permeability of vacuum, and all geometrical factors are illustrated in Figure 1. Equations (1) and (2) are obtained in a straightforward manner using an approach similar to that of *Uman et al.* [1975]. In (1) the first and fourth terms are generally called the electrostatic field, the second and fifth the induction or intermediate field, and the remaining two terms the radiation field. In (2) the first term is the induction field and the second, the radiation field. The effects of the perfectly conducting ground plane on the electric and magnetic fields due to the source dipole are included by replacing the ground plane by an image current dipole at distance $-z'$ beneath the plane, as shown in Figure 1 [*Stratton*, 1941]. The electric and magnetic fields due to the image dipole may be obtained by substituting R_I for R and $-z'$ for z' in (1) and (2) above.

In this paper we examine only the fields of a typical subsequent return stroke because it is subsequent strokes with which *Lin et al.* [1980] have tested their model. Subsequent strokes are more easily modeled than first strokes because in contrast to firsts, subsequents have few if any branches, have relatively constant return stroke velocities, and are probably initiated at ground level rather than by upward-going leaders [*Schonland*, 1956].

The model of *Lin et al.* [1980] postulates that the return stroke current is composed of three components: (1) a short-duration upward-propagating pulse of current of constant magnitude and waveshape associated with the electrical breakdown at the return stroke wavefront and responsible

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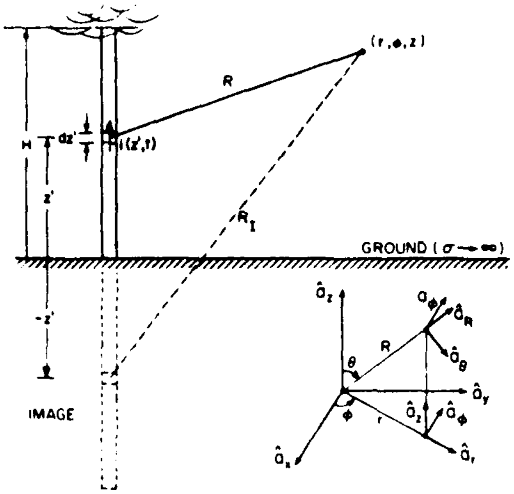

Fig. 1. Geometry for field computations.

for the return stroke peak current; the pulse is assumed to propagate at a constant velocity; (2) a uniform current which may already be flowing (leader current), an assumption we use in this paper, or it may start to flow soon after the commencement of the return stroke; and (3) a 'corona' current caused by the downward movement of the charge initially stored in the corona sheath around the leader channel and discharged by the passage of the return stroke wavefront. These three current components are illustrated in Figure 2.

Two observations form the basis for a modification of the model of *Lin et al.* [1980]:

1. At the time that the research of *Lin et al.* [1980] was done, subsequent strokes were thought to have both luminosities (hence, by implication, currents) and return stroke velocities that were invariant with height [*Schonland*, 1956]. However, *Jordan and Uman* [1980] have since shown that subsequent stroke initial peak luminosity varies markedly with height, decreasing to half-value in less than 1 km above ground. The implication of this result is that the breakdown pulse current (component (1) in the model) must also decrease with height.

2. When the breakdown pulse reaches the top of the channel, the model of *Lin et al.* [1980] predicts a field change of opposite polarity to that of the initial field, the waveshape of the field change being a 'mirror image' of the initial field change. A detailed discussion of the mirror image effect is given by *Uman et al.* [1975]. It is observed occasionally in the fields from first return strokes but almost never in the fields from subsequent return strokes [*Lin et al.*, 1979]. If the breakdown pulse current is allowed to decay with height so that it has a negligible value when it reaches the end of the channel, the mirror image should no longer be manifest in the calculated fields.

In view of observations 1 and 2 above, we propose the following modification to the model of *Lin et al.* [1980]: the breakdown pulse current is allowed to decrease with height above the ground; all other features of the original model remain unchanged. As we shall see, the fields at ground level produced by the modified model are essentially the same as those due to the original model except for the absence of the mirror image. However, the fields in the air, especially at close ranges, differ considerably.

We first consider the calculation of the electric and magnetic fields of a typical subsequent stroke using the original model of *Lin et al.* [1980]. We then repeat the calculation for the modified version of the model. The subsequent stroke used in this study is that for which the following data are given in Figure 11 of *Lin et al.* [1980]: both measured and calculated fields at ranges of 2 km and 200 km at ground level and calculated current at ground level. This calculated current and the three components which constitute it are shown in Figure 3. The rise-to-peak of the breakdown pulse component has been altered from that given by *Lin et al.* [1980] so as to be consistent with the measurements of *Weidman and Krider* [1978]. The salient parameters of the current used in the field calculations for the case of a constant breakdown pulse current are (1) breakdown pulse current: increase from 0 to 3 kA in 1.0 μs, followed by a fast transition to a peak value of 14.9 kA at 1.1 μs, half value at 3.8 μs, and zero at 40 μs; the breakdown

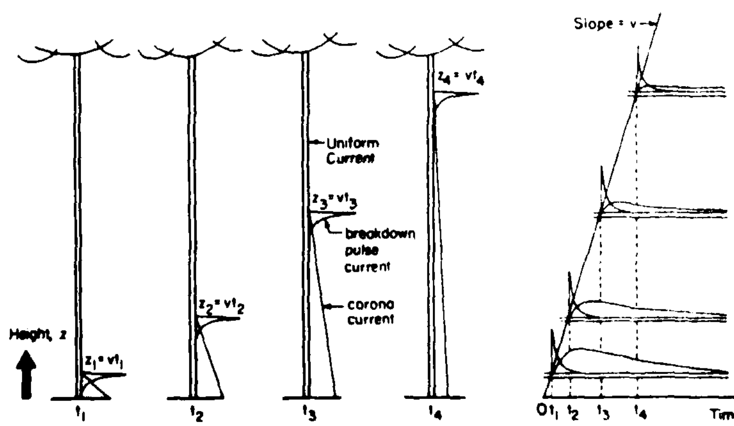

Fig. 2. Current distribution for the model of *Lin et al.* [1980] in which the breakdown pulse current is constant with height. The constant velocity of the breakdown pulse current is v. Current profiles are shown at four different times, t_1 through t_4, when the return stroke wavefront and the breakdown pulse current are at four different heights z_1 through z_4, respectively.

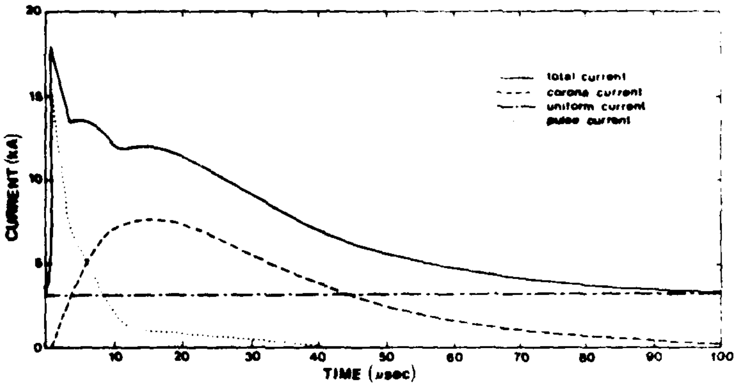

Fig. 3. Return stroke current components at ground calculated from measured electric and magnetic fields for a typical subsequent stroke.

pulse current propagates upward with an assumed constant velocity of 1×10^8 m/s, (2) uniform current: 3100 A, and (3) corona current injected per meter of channel: $I_0 e^{-z'/\lambda}(e^{-\alpha t} - e^{-\beta t})$, with $I_0 = 21$ A/m, $\lambda = 1500$ m, $\alpha = 10^5$ s^{-1}, and $b = 3 \times 10^6$ s^{-1}. The initial charge stored on the leader and lowered by the return stroke is 0.3 C. The channel length is 7.5 km. In the modified version of the model we use a breakdown pulse current whose amplitude decreases with height as $e^{-z'/\lambda}$, with $\lambda \approx 1500$ m; that is, the breakdown pulse current decreases with height in exactly the same way as does the corona current. All other parameters for the modified model are the same as those for the original model.

Since both first and subsequent strokes probably have initial currents which decrease with height [*Schonland*, 1956; *Jordan and Uman*, 1980], and since the measured waveshapes of first and subsequent stroke fields at ground level are qualitatively similar [*Lin et al.*, 1979], one would also expect the airborne subsequent stroke fields calculated using the modified model to be qualitatively similar to airborne first stroke fields.

RESULTS

Calculated vertical and horizontal electric fields are shown in Figures 4*a* and 4*b*, respectively, and calculated magnetic fields in Figure 4*c*. Solid lines represent the original model of *Lin et al.* [1980] and dashed lines the modified version of the model in which the breakdown pulse current decreases with height. All zero times on the figures indicate the time at which the return stroke current originates at ground level. The waveforms at the field points begin after the appropriate propagation time delay. The intersections of the slanted solid lines with the horizontal dotted lines at various heights indicate the times at which the return stroke wavefront passes those heights. A number of features of the calculated waveforms are worthy of note:

1. With the exception of the absence of the abrupt field changes associated with the end of the channel, the fields on the ground at all distances and the fields on the ground and in the air beyond about 10 km are not much influenced by the breakdown current pulse decrease with height. This is the case because the initial parts of these field waveforms are radiated by the breakdown current pulse while it is very close to the ground and near its maximum amplitude, while later portions of the field waveform are primarily due to the uniform and corona currents which are the same in the original and modified models. Hence it follows that ground-based or distant airborne measurements cannot be used to test the validity of the model modification introduced here.

2. The abrupt field changes associated with the unattenuated breakdown pulse current reaching the idealized ends of the real and image channels [*Uman et al.*, 1975] do not occur when that pulse current is attenuated with height so that it does not have an appreciable magnitude when it reaches the channel end. As noted earlier, the fact that these abrupt changes do not often occur in the experimental data [*Lin et al.*, 1979] was one of the reasons for the proposed modification to the original model of *Lin et al.* [1980].

3. At ranges less than about 200 m the horizontal electric and the magnetic field components above ground attain initial peak values at about the time at which the return stroke breakdown pulse current is at the same altitude as the field point. The vertical electric field component undergoes a sharp decrease at this point. The maximum electric and magnetic fields are due to the charge and current, respectively, associated with the breakdown pulse component at about the time of its closest approach to the field point. The peak electric field is essentially electrostatic, the peak magnetic field essentially induction. The initial peak field present in measurements made beyond a few kilometers and associated with the radiation field component of the breakdown pulse current is present in the close electric and magnetic fields but is small compared with the electrostatic and induction fields, respectively. The effect of the decrease of the breakdown pulse current with height is primarily to decrease the magnitude of the initial electrostatic and induction peaks.

4. At ranges less than about 200 m the vertical electric field above ground is bipolar for the unattenuated pulse current due to the passage from below to above of the charge associated with the breakdown pulse current. As one moves farther away from the channel, is near the ground, or considers a pulse which decays with height, this bipolar effect is reduced. On the ground near the channel the electric field is always unipolar and of opposite polarity as compared to the initial bipolar field, since the charge motion is always at a height above that of the field point.

5. At ranges less than about 1 km the peak value of the horizontal electric field above ground is larger than the associated vertical electric field. The horizontal and vertical

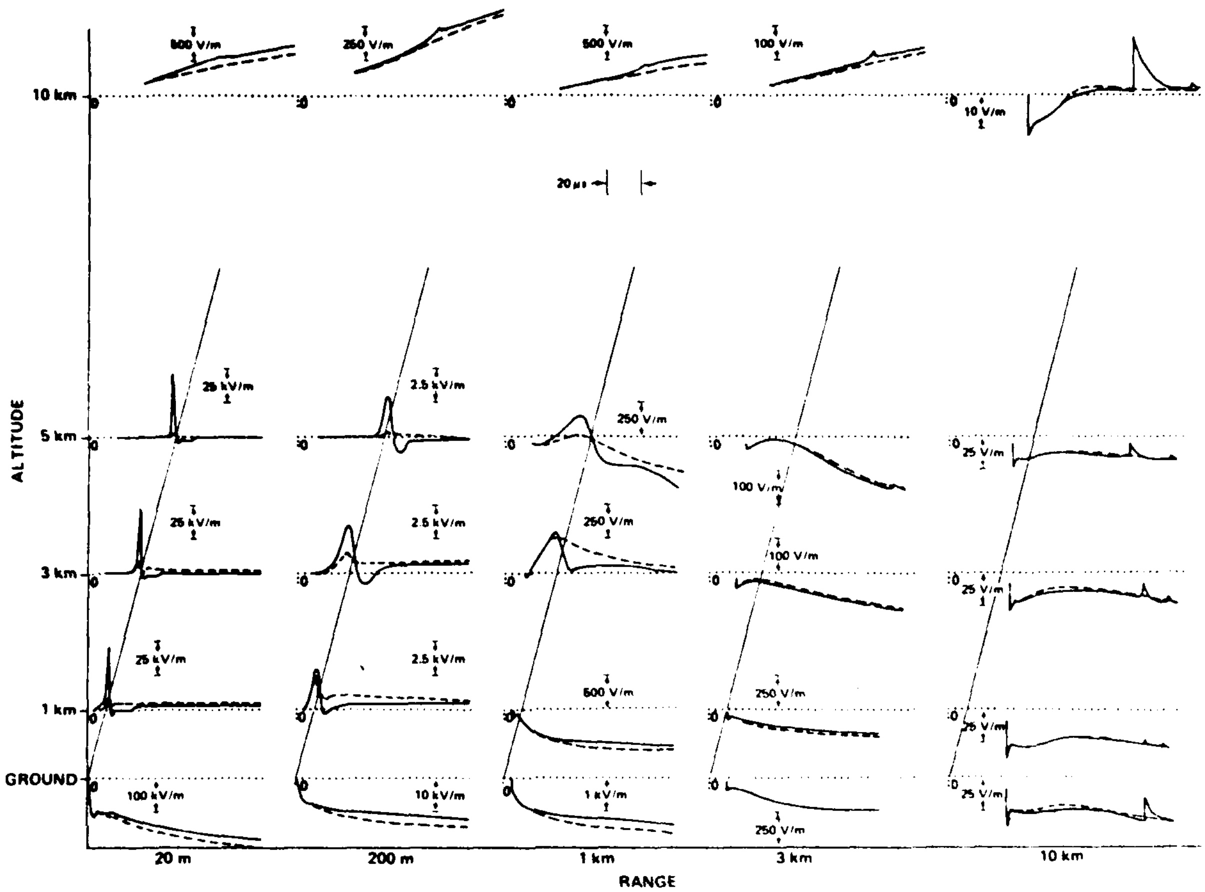

Fig 4a. Calculated vertical electric fields for a typical subsequent return stroke. The solid lines represent the original model in which the breakdown pulse current is constant with height; the dashed lines the modified model in which it decreases with height.

fields above ground are roughly equal in peak magnitude in the 3 km range, and the vertical field is larger beyond about 10 km.

6. At ranges greater than 10 km the magnetic field and the vertical electric field are relatively weak functions of altitude, whereas the horizontal electric field increases roughly linearly with altitude. The magnetic field and the vertical electric field are height independent as long as the difference between the propagation paths from the source dipole and its image is much less than the wavelength of the highest significant frequency component of the electromagnetic radiation from the source, a condition which is met to a reasonable approximation at a range of about 10 km at altitudes below about 3 km for the current waveshapes used in the model. Hence measurements of distant magnetic and vertical electric fields made simultaneously on the ground and in the air provide a simple means of calibrating the airborne measurements.

7. The initial nonzero value associated with the waveforms, which can be clearly seen in Figures 4a, 4b, and 4c at, for example, 10 km, is due to the induction field from the uniform current component (component 2 in the model) assumed to exist at the time at which the breakdown pulse current is initiated at ground level. We associate the uniform current with the dart leader which preceeds the return stroke. The electrostatic field value at the time of the initiation of the return stroke at ground due to the current flow prior to that time is unknown and hence is not included in the calculated fields. In the work by *Lin et al.* [1980] the initial field value was plotted as zero, since the actual value could not in general be determined from the type of measurements made by *Lin et al.* [1979].

DISCUSSION

In this paper we have presented the first detailed estimates of airborne electric and magnetic fields due to lightning. We have used the original model of *Lin et al.* [1980] and also a modified version based on observations of *Lin et al.* [1979] and of *Jordan and Uman* [1980]. The new version of the model (1) results in fields which do not exhibit abrupt changes associated with the breakdown pulse current reaching the top of the channel and (2) can be expected to produce an initial luminosity which decreases with height above the ground. Though the individual currents which define the modified model are not unique (see discussion by *Lin et al.* [1980]), it is likely that the total current, which results in accurate prediction of ground-based fields and is consistent with (1) and (2) above, predicts airborne fields which are at least qualitatively correct.

We have modeled the return stroke channel as a straight vertical antenna. An actual return stroke channel is charac-

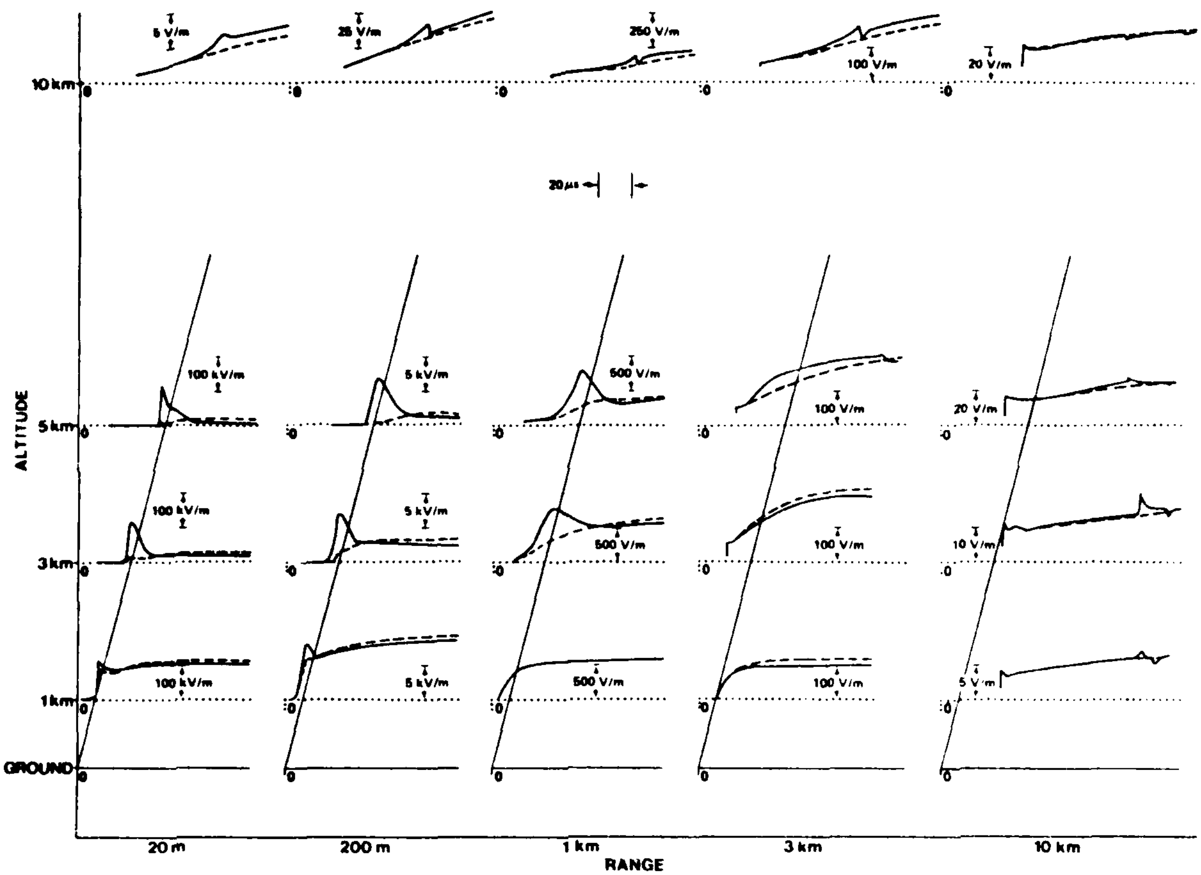

Fig. 4b. Calculated horizontal electric fields for a typical subsequent return stroke. The solid lines represent the original model in which the breakdown pulse current is constant with height; the dashed lines the modified model in which it decreases with height.

terized by tortuosity on a scale from less than 1 m to over 1 km [e.g., *Evans and Walker*, 1963; *Hill*, 1968]. *Hill* [1969] and *LeVine and Meneghini* [1978], using simple models, have investigated the effects of channel tortuosity on distant radiation fields. LeVine and Meneghini find that the waveforms computed for the case of a tortuous channel have finer structure than those for a straight channel, resulting in a frequency spectrum for the tortuous channel that has larger amplitude at frequencies above about 100 kHz. Hill shows that horizontal channel sections radiate significantly for frequencies above 20–30 kHz but does not compare the radiation from horizontal channel sections with that from vertical sections. The effect of using a tortuous channel to model the lightning return stroke fields at close range has been investigated by *Pearlman* [1979], again using a simple model. His results indicate that channel tortuosity has little effect on the close fields. Since the peaks in the close electric and magnetic fields are due to the charge and current, respectively, associated with the breakdown pulse current (as discussed in (3) of the previous section), we suggest on physical grounds that the general shapes of the close fields should not be greatly different from those shown. However, the peak fields at close range should occur at the time the breakdown pulse reaches the point of closest approach to the field point, and thus the distance of closest approach replaces the range in Figures 4*a*, 4*b*, and 4*c*.

Available data on airborne field measurements are limited to the observations of *Pitts and Thomas* [1980] and of *Baum* [1980]. Pitts and Thomas do not appear to have any data on return stroke fields. Baum presents airborne measurements made on first and subsequent return stroke electric and magnetic fields. He gives one typical first and one typical subsequent return stroke electric field waveform. He does not, however, make an independent measurement of the distance to the lightning flashes he records. Rather, he uses the values of the observed airborne initial peak fields and the average observed values on the ground as a function of distance obtained by *Lin et al.* [1979] to estimate the range. We have shown in this paper that the peak radiation fields for distances beyond about 10 km are about the same in the air and on the ground. However, the comparison with average values of the fields on the ground as a function of distance can lead to range errors of two or three, since individual field values may differ from the average by this factor [*Lin et al.*, 1979]. If we do use Baum's ranging technique, the subsequent stroke waveform he gives is at a range of about 20 km. The aircraft was at an altitude between 3 km and 5 km. The measured airborne electric field is very similar to typical measured fields on the ground at that range, as expected from the theory presented in this paper. A test of the validity of the predicted fields and hence the model awaits measurement at close range of simultaneous

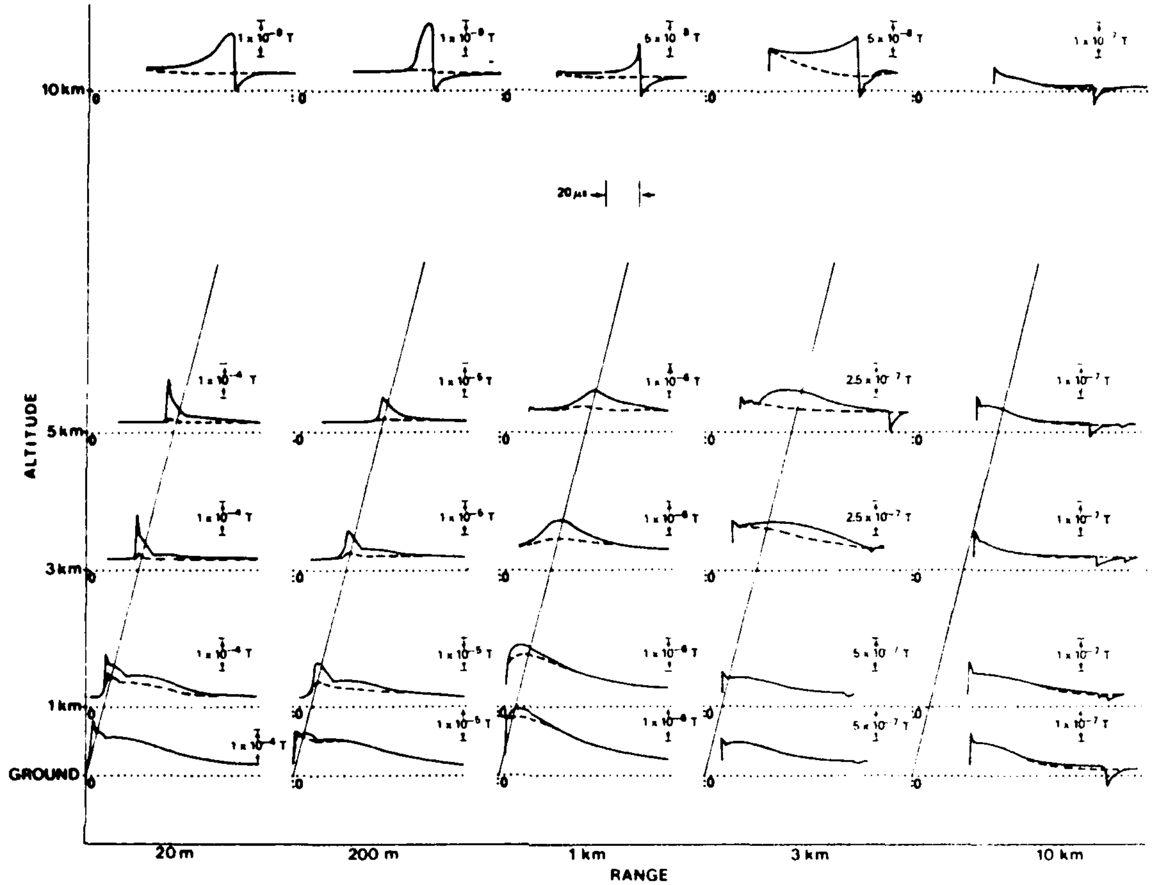

Fig. 4c. Calculated magnetic fields for a typical subsequent return stroke. The solid lines represent the original model in which the breakdown pulse current is constant with height; the dashed lines the modified model in which it decreases with height.

ground-based and airborne return stroke electric and magnetic fields.

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APPENDIX 3

A Comparison of Lightning Electromagnetic Fields with the Nuclear Electromagnetic Pulse in the Frequency Range 10^4-10^7 Hz

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A Comparison of Lightning Electromagnetic Fields with the Nuclear Electromagnetic Pulse in the Frequency Range 10^4–10^7 Hz

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Abstract—**The electromagnetic fields produced by both direct lightning strikes and nearby lightning are compared with the nuclear electromagnetic pulse (NEMP) from an exoatmospheric burst. Model calculations indicate that, in the frequency range from 10^4 to near 10^7 Hz, the Fourier amplitude spectra of the return stroke magnetic fields near ground 1 m from an average lightning strike will exceed that of the NEMP. Nearby first return strokes at a range of about 50 m, if they are severe, produce electric-field spectra near ground which exceed that of the NEMP below about 10^6 Hz, while the spectra of average nearby first return strokes exceed that of the NEMP below about 3×10^5 Hz. Implications of these results for aircraft in flight are discussed.**

Key Words—**Lightning, EMP, electromagnetic fields, amplitude spectra, aircraft.**

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I. INTRODUCTION

A SERIES of recent articles describe the threat to the United States command, control, and communications (C^3) network from a nuclear electromagnetic pulse (EMP or NEMP) generated by an exoatmospheric nuclear explosion. Broad [1]-[3] has critically examined the various technical and political problems surrounding NEMP; Lerner [4], [5] has discussed the damaging effects of NEMP on the C^3 network and on nuclear power plants; and Raloff [6], [7] has considered the threat posed by NEMP and the implementation of defensive strategies. It has often been stated [4], [6], [8] that the effects of NEMP are comparable to, or greatly exceed, those of the most severe lightning. For example, Holden [8] states that "the EMP is a microsecond burst of electromagnetic energy, a hundred times more powerful than a lightning bolt." As far as we are aware, the claims that NEMP effects almost always exceed those of lightning are not quantitatively justified in the literature. On the other hand, a recent letter to the Editor of the IEEE SPECTRUM [9] cites references to the lightning literature to support the view that lightning effects can be equivalent to or exceed those of the NEMP.

The effects of NEMP from an exoatmospheric burst will be felt over a large geographical area, whereas the effects of a single lightning discharge are local. Nevertheless, the frequency of direct and nearby strikes to sensitive earthbound structures like nuclear power plants, to electric transmission and distribution systems, and to aircraft in flight is sufficiently high to warrant a careful assessment of the lightning hazard. Here we present frequency-domain comparisons of the electric and magnetic fields near ground due to model lightning return strokes with those of the NEMP from an exoatmospheric burst. The applicability of these results for altitudes at which, for example, aircraft operate, is presently a matter of speculation due to the paucity of airborne measurements, as we will discuss. We will show that, in the frequency range from 10^4 to near 10^7 Hz, the calculated Fourier amplitude spectra of the return stroke magnetic fields near ground 1 m from an average lightning strike will exceed that of the NEMP; and that electric field spectra near ground of severe nearby first return strokes at 50 m exceed that of the NEMP below about 10^6 Hz and spectra of average nearby first return strokes are greater below about 3×10^5 Hz. To the extent that fields in the frequency ranges in which lightning spectra exceed that of NEMP represent a hazard by, for example, exciting resonances in a structure which couple damaging voltages and currents to electronics in the interior of that structure [10], [11], lightning effects can apparently be as severe as those due to the NEMP.

II. LIGHTNING

Recently, it has been reported that the electric and magnetic fields produced by all important lightning discharge processes contain significant variations on a submicrosecond time scale [12]-[18]. The existence of these field components, in turn, implies that the currents which produce them contain large submicrosecond variations [13], [15], [16], [19]. The few direct wide-band measurements of lightning currents during strikes to airplanes in flight show submicrosecond rise times for current pulses in the 100-A range [20], [21]. These pulses are probably associated with small cloud discharge processes.

Uman *et al.* [22] have calculated the distant electric and magnetic radiation fields produced at ground level by a fixed current waveshape propagating up a straight vertical channel

$$E_{rad}(D, t) = -\frac{\mu_0 v}{2\pi D} \cdot i(t - D/c)\mathbf{a}_z, \qquad t \geqslant D/c \tag{1}$$

$$H_{rad}(D, t) = \frac{v}{2\pi c D} \cdot i(t - D/c)\mathbf{a}_\phi, \qquad t \geqslant D/c \tag{2}$$

where $i(t)$, $t \geqslant 0$, is the current at time t, v is the velocity with which the current pulse propagates up the channel, D is the horizontal distance from the channel to the point at which the field is measured, c is the speed of light, μ_0 is the permeability of free space, z is the vertical coordinate, and ϕ is the azimuthal coordinate. The best available models for the current in the return stroke phase of a cloud-to-ground discharge [23], [24] (see [25], [26] for a general review of lightning discharge phenomena) have model currents which, in the time domain, produce electric and magnetic fields in good agreement with wide-band (dc to about 2 MHz) time-domain measurements made at ground level. For these models, (1) and (2) provide a good approximation to the relation between the initial return stroke radiation field and the initial return stroke current. Weidman and Krider [16] have measured the maximum rate-of-rise of the initial return stroke radiation field for first strokes and find a mean of about 30 V/m·μs normalized by an inverse range relation to a distance of 100 km. This mean value, when substituted in (1), with an assumed return stroke velocity of 10^8 m/s, leads to a calculated mean maximum rate-of-rise of the return stroke current of about 150 kA/μs, a value which is representative of the current just above ground. The maximum values of maximum rate-of-rise of field and current from 97 measured first strokes are about 2.5 times the mean [16].

Lightning return stroke current waveforms have been directly measured during strikes to instrumented towers in Switzerland [27], in Italy [28], and in South Africa [29]. Unfortunately, currents to tall towers do not necessarily provide a good estimate of the current encountered by small earthbound structures or of the current in the lightning channel above ground because of the effects of the relatively long upward-propagating leader which is initiated by the tower and because of the effects of the tower inductance, capacitance, and relatively large ground impedance characteristic of the mountainous terrain where most measurements have been made. The upward-propagating discharge, for example, could cause a slower overall current rise time at the tower than a comparable strike to normal ground and could conceivably alter or mask the fast current components. This effect should be more pronounced for first return strokes than for subsequent strokes, since the latter are thought not to have long upward-propagating leaders. Berger *et al.* [27] found that the median peak current for first return strokes which lowered negative charge to a tower in Switzerland was 30 kA and that the median maximum rate-of-rise of the current was 12 kA/μs. The corresponding values at the 5-percent level were 80 kA and 32 kA/μs. For negative strokes subsequent to the first in multiple-stroke flashes, the median peak current was 12 kA, and the median maximum rate-of-rise was 40 kA/μs. Subsequent strokes at the 5-percent level had a peak current of 30 kA and a maximum rate-of-rise of 120 kA/μs. It is interesting to note that the subsequent stroke currents reported in [27] have shorter overall rise times and larger maximum rates-of-rise than first strokes. This result should be contrasted with the electric radiation field measurements made by Weidman and Krider [13], [16], who report no significant differences in the maximum rates-of-rise of first and subsequent stroke fields. The tower on which Berger *et al.* [27] made their measurements was on top of Mt. San Salvatore in Switzerland.

TABLE I A
CURRENT PARAMETERS FOR AN AVERAGE FIRST RETURN STROKE OBTAINED FROM REMOTE FIELD MEASUREMENTS IN ACCORDANCE WITH THE PROCEDURE OUTLINED IN [23], [24]

Current at ground

Time (μs)	Current (kA)
0.0	0.0
100.0	5.0
105.0	20.0
105.1	35.0
107.0	18.0
112.5	25.0
120.0	27.0
140.0	18.0
160.0	12.4
200.0	5.0
300.0	0.0

given by the following parameters

(1) Breakdown pulse current with velocity 1×10^8 m/s:

t(μs)	I_p(kA)
0.0	0.0
5.0	15.0
5.1	30.0
7.0	8.0
15.0	2.0
40.0	0.0

The pulse decays exponentially with height above the ground with a decay constant $\lambda_p = 2.0 \times 10^3$ m

(2) Uniform current $I_u = 5$ kA

time duration = 0.3 ms; turn-on time = 0.1 ms

(3) Corona current per unit length is $I_c = I_{c0}\, e^{-z/\lambda}(e^{-\alpha t} - e^{-\beta t})$ A/m

where,

$I_{c0} = 50.0$ A/m

$\lambda = 2.0 \times 10^3$ m

$\alpha = 1 \times 10^5\ s^{-1}$

$\beta = 3 \times 10^6\ s^{-1}$

TABLE I B
CURRENT PARAMETERS FOR AN AVERAGE FIRST RETURN STROKE OBTAINED FROM TOWER MEASUREMENTS [27]

Time (μs)	Current (kA)
0.0	0.0
3.0	3.2
5.0	7.0
6.5	14.0
7.8	21.0
8.3	28.0
8.6	32.0
9.0	34.0
10.0	35.0
40.0	28.0
80.0	21.0
250.0	0.0

TABLE II A
CURRENT PARAMETERS FOR AN AVERAGE SUBSEQUENT RETURN STROKE OBTAINED FROM REMOTE FIELD MEASUREMENTS [23], [24]

Current at ground

Time (μs)	Current (kA)
[illegible]	0.
100.0	3.[illegible]
101.0	6.
[illegible]1.1	18.0
103.8	13.5
106.5	13.5
111.0	11.6
120.0	11.2
[illegible]	[illegible]
200.0	[illegible]
300.[illegible]	[illegible]

given by the following parameters

(1) Breakdown pulse current with velocity $1 \times 10^{[illegible]}$ m/s.

t(μs)	I_p(kA)
0.[illegible]	[illegible]
1.[illegible]	[illegible]
[illegible].1	[illegible]
3.[illegible]	[illegible]
11.0	[illegible]
[illegible]	[illegible]

The pulse decays exponentially with height above the ground with a decay constant, $\lambda_p = 1.5 \times 10^3$ m

(2) Uniform current $I_u = 3$ kA

time duration = [illegible] ms; turn-on time = [illegible] ms

(3) Corona current per unit length is $I_c = I_{c0}\, e^{-z/\lambda}(e^{-\alpha t} - e^{-\beta t})$ A/m

where,

I_{c0} = [illegible] A/m

$\lambda = 1.5 \times 10^3$ m

α = [illegible]

β = [illegible]

TABLE II B
CURRENT PARAMETERS FOR AN AVERAGE SUBSEQUENT RETURN STROKE OBTAINED FROM TOWER MEASUREMENTS [27]

Time (μs)	Current (kA)
[illegible]	0.
[illegible]	7.[illegible]
[illegible]	14.4
[illegible]	18.0
[illegible]	13.8
[illegible]	11.7
[illegible]	10.8
80.[illegible]	7.2
250.[illegible]	0.0

On the other hand, the tower used in the South African study [29] was situated on a comparatively flat terrain. In [29], a maximum current rate-of-rise of 180 kA/μs was reported for a subsequent stroke, although the total sample size was only 11 flashes.

Berger *et al.* [27] have computed "mean lightning current waveshapes" for first and subsequent negative strokes. These were determined by first normalizing all the measured waveforms to a peak value of unity and then averaging the measured values at each time. If this "mean waveshape" is scaled up in current to produce a large-amplitude waveform, as we shall do to model a severe lightning, the rate-of-rise necessarily scales also. On the other hand, the reported tower measurements do not show a very strong correlation between the peak current and the rate-of-rise of current [27], [30].

There is general agreement that the mean peak current during strikes to normal objects on the ground is in the 20–40-kA range, and that peak currents of 175-, 25 kA are present in about 1 percent of the strikes [31].

To calculate return stroke fields for comparison with the NEMP, we will use first and subsequent return stroke current waveforms that are inferred from both the remote electromagnetic-field measurements and the tower measurements. Specification of currents for average first and subsequent strokes is given in Tables I and II. The peak current value for an average first stroke is chosen to be 35 kA, and for an average subsequent stroke, 18 kA. The currents derived from the electromagnetic-field measurements [23], [24], differ from the directly measured currents on Mt. San Salvatore [27] primarily in the relatively slow rate-of-rise of first stroke current in the tower measurements compared to that derived from the fields. Severe lightning currents are obtained by multiplying by a factor of *five* both the typical currents derived from electromagnetic fields [23], [24] and the "mean lightning current waveshapes" from tower measurements [27] given in Tables I and II. Although the peak value of the currents determined this way are representative of measured severe lightning [31], the rate-of-rise we use for severe lightning, five times the average value, may be excessive if the rate-of-change of current does not scale with the current. As noted previously, no strong correlation has been found between peak current and rate-of-change of current in the tower measurements [27], [30]. No data have been published on this correlation for the currents derived from the fields, and, as noted previously, the largest value of the maximum rate-of-rise of the electric radiation field for 97 first strokes was only about 2.5 times the mean [16].

III. NEMP

The characteristics of the NEMP are a function of whether the nuclear event is in or out of the atmosphere and the distance from it. A thorough survey of the mechanisms by which the NEMP is generated, the details of the coupling of the NEMP to a variety of systems, and the response of those systems is found in two volumes of collected papers [10], [11]. Reasonable approximations to the NEMP waveform at the surface of the earth or at aircraft altitude due to an exoatmospheric burst have been given in Lee [11]. For the present study, we choose the exoatmospheric burst NEMP waveform from Lee [11] which appears to be the choice of most NEMP researchers

$$E(t) = E_0[e^{-\alpha t} - e^{-\beta t}], \qquad t \geq 0 \tag{3}$$

$$H(t) = H_0[e^{-\alpha t} - e^{-\beta t}], \qquad t \geq 0 \tag{4}$$

with $E_0 = 5.2 \times 10^4$ V/m, $H_0 = 1.4 \times 10^2$ A/m, $\alpha = 4.0 \times 10^6$ s^{-1}, and $\beta = 5.0 \times 10^8$ s^{-1}.

IV. COMPARISONS

A. Direct Strike and NEMP

To compare the fields from lightning direct strikes with NEMP fields, we must choose an example object to be struck. Let us consider the fields at the surface of a hypothetical cylindrical metallic aircraft fuselage of radius r. We choose the aircraft as an example because of its considerable practical importance. If a lightning return stroke attaches directly to this aircraft and the current flows uniformly along the fuselage, the magnetic-field intensity at the surface will be about

$$H = \frac{I}{2\pi r} \tag{5}$$

where I is the lightning current and where the total field has been approximated as magnetostatic. Obviously, the field will be the same at a distance r from the axis of any structure much longer than r which uniformly carries the current, and hence, the results to be obtained are generally applicable. If the aircraft is struck by an average first return stroke with a peak current of about 35 kA, the peak magnetic field at the surface with an assumed radius of 1 m will be about 5.6 × 10^3 A/m. A 175-kA severe stroke will produce a peak field of about 2.8×10^4 A/m. If about half of the lightning field rises to peak in about 0.1 μs, as suggested by the electromagnetic-field measurements of Weidman and Krider [13], [16], then the maximum rate of change of the magnetic field from an average first stroke will be about 2.8×10^{10} A/m·s and from a severe stroke will be about 1.4×10^{11} A/m·s. The peak NEMP field, 2.8×10^2 A/m, can be obtained by multiplying (4) by a factor of 2, to take account of the reflection of the NEMP plane wave from the metallic surface of the aircraft. The maximum field rate-of-change for NEMP is 1.4×10^{11} A/m·s and exists for a time of the order of a nanosecond. The return stroke peak fields from normal lightning exceed those of the NEMP by a factor of about 20. The NEMP maximum rate-of-change exceeds that of normal lightning by a factor of about 5 and is about equal to that of severe lightning.

We now examine how the time-domain parameters derived above for lightning and NEMP are reflected in the Fourier amplitude spectra for the two events. Again we use the example of the fields on the surface of an aircraft, the calculated lightning fields, however, being essentially the same at comparable distance from any direct strike. For the computations involving currents derived from electric and magnetic fields, both the radiation and induction field terms in the general field equations have been included [23], [24], although (5), with the currents given in Tables IA and IIA, provides a good approximation to the end result. In calculations involving currents from tower measurements, the magnetic field is calculated directly from (5).

Figs. 1 and 2 show the Fourier amplitude spectra of the time-domain magnetic fields produced by currents given in Tables I and II for both average and severe return strokes derived from both tower and remote field measurements. The current waveforms are composed of straight-line segments between the points given in Tables I and II and are digitized at 0.005-μs intervals for the calculation of the Fourier amplitude spectra. The spectra inferred from the electromagnetic-field measurements are larger above 10^5 Hz than those derived from the tower data for first strokes, due to the relatively slow first-stroke current rate-of-rise measured on towers, but the two spectra are similar for subsequent strokes. For average return strokes, the spectral amplitudes for the first and subsequent stroke fields determined from remote electromagnetic measurements, and the subsequent-stroke measured tower current, are equal to the NEMP at a frequency near

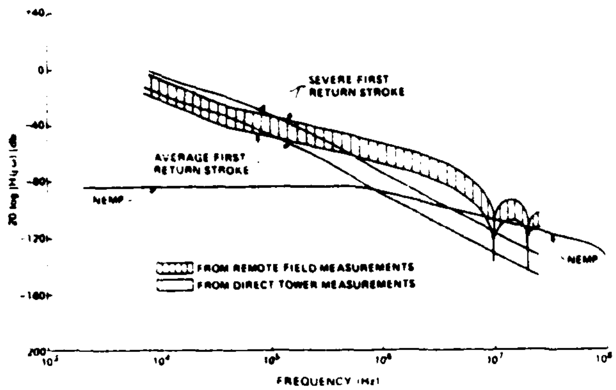

Fig. 1. Magnetic-field Fourier amplitude spectra for a direct strike by an average and a severe first return stroke from both tower and remote field measurements and for NEMP. The dips in the remote field data at 1×10^7 and 2×10^7 Hz are due to the large linear current transition taking place in 0.1 μs during the current rise to peak. Since real waveshapes do not have such linear transitions, the dips in the spectra are artificial.

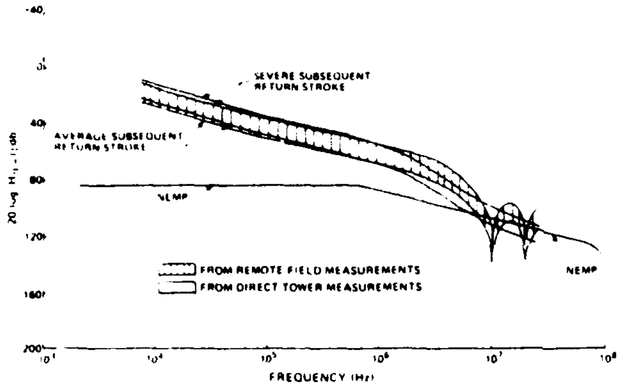

Fig. 2. Magnetic-field Fourier amplitude spectra for a direct strike by an average and a severe subsequent return stroke from both tower and remote field measurements and for NEMP. The dips in the remote field data at 1×10^7 and 2×10^7 Hz are due to the large linear current transition taking place in 0.1 μs during the current rise to peak. Since real waveshapes do not have such linear transitions, the dips in the spectra are artificial.

10^7 Hz and exceed the NEMP at frequencies below that value. For above-average return strokes, the lightning spectra exceed the NEMP spectra to frequencies above 10^7 Hz.

The preceding comparisons between lightning and NEMP fields are, strictly speaking, applicable only near ground. We use the example of an aircraft because of its practical importance, and, for that reason, a discussion of the fields above ground is in order. An aircraft in flight would probably not encounter the full return stroke current which would flow through a structure on the ground since the return stroke current will probably decrease with height [24]. In fact, Clifford and Kasemir [32] argue that most strikes to aircraft are not return strokes but are triggered by the aircraft and are some sort of in-cloud discharge with a rate-of-change of current an order of magnitude less than that of the average return strokes we are considering. Clifford and Kasemir [32] contend that aircraft are only occasionally involved with return strokes, although the total data from instrumented aircraft, on which this opinion is based, are meager. In any event, relatively large return stroke currents at ground level may well still produce currents at aircraft operational altitudes to cause fields equivalent to the NEMP at frequencies below about 10^7 Hz. More important is the observation that both the in-cloud discharge processes which precede stepped leaders in ground flashes and certain pulses in intracloud lightning discharges produce Fourier amplitude spectra measured near ground for distant discharges comparable to those of distant return strokes [17], implying that there are in-cloud events which produce close fields in the cloud equivalent to close return stroke fields near ground. These in-cloud processes can be expected to interact with aircraft. An accurate assessment of the probability of aircraft involvement with different types and phases of lightning awaits further research. Finally, it is worth noting that the NEMP wavefront is plane while the lightning field is circular and that lightning channel attachment to an aircraft may alter the behavior of traveling and reflected waves on the aircraft structure from the free field NEMP case, and hence there may be additional factors in the comparison which we have not considered.

B. Nearby Lightning and NEMP

For the direct lightning strike, we have compared the magnetic field at an aircraft surface with the NEMP. For a nearby flash, we will compare the electric fields. The fields are those which would exist in the absence of the aircraft. We will plot spectra only for the severe first return stroke at ground level. In Fig. 3, we show the NEMP spectrum calculated from the expression given in (3) along with three electric-field amplitude spectra for severe first return strokes which strike the ground 50 m from the observation point. The three lightning amplitude spectra are: 1) the average first stroke electric radiation field spectrum measured by Weidman et al. [17] for return strokes at about 50 km extrapolated to 50 m using an inverse distance relationship and multiplied by a factor of 5 to simulate a severe stroke; 2) the electric radiation field spectrum at 50 km calculated using the model of Master et al. [24] with the currents in Table IA multiplied by a factor of 5 and extrapolated to 50 m using an inverse distance relationship; and 3) the total electric-field spectrum at 50 m calculated using the model [24] with the currents in Table IA multiplied by a factor of 5.

The calculated and the measured radiation field spectra at 50 km extrapolated to 50 m are essentially identical. The amplitude spectrum computed for the total electric field of a 175-kA lightning at 50 m is equal to the extrapolated radiation field near 10^7 Hz and is greater for lower frequencies because the electrastatic and induction components of the total field add to the radiation component. The spectrum of the total electric field exceeds that of the NEMP below about 10^6 Hz. For an average nearby first return stroke, the total electrical field spectrum exceeds that of the NEMP below about 3×10^5 Hz.

The nearby discharge has been assumed to be at a distance of 50 m because this is about the range at which an earth-bound structure or an aircraft in flight would be expected to become involved in a typical direct strike. The closest distance at which the lightning return stroke fails to attach to a ground-

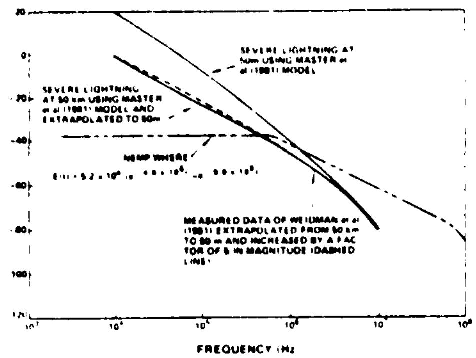

Fig. 3. Electric-field Fourier amplitude spectra for a severe first return stroke at 50 m and for NEMP. For the purpose of clarity, dips in the computed 50-km spectrum, similar to those shown in Figs. 1 and 2, have been omitted.

based structure may be derived from the "striking distance" concept developed by Gold [33].

Fig. 3 shows the vertical electric field at ground level. Master *et al.* [24] have computed the horizontal and vertical electric fields and the horizontal magnetic fields above ground level. The validity of these calculations, however, depends on the validity of the assumed currents above ground level. Field measurements above ground are needed before the adequacy of the calculated nearby return stroke field environment above ground can be evaluated. Further, future calculations should include the effects of channel tortuosity which are not taken into account in the model [23], [24] used in this paper. Although nearby return stroke fields may well decrease with altitude to the point that they are unimportant compared to the NEMP, in-cloud processes, as noted earlier, can produce distant fields near ground with comparable Fourier amplitude spectra to return strokes [17], implying that nearby in-cloud processes at aircraft altitudes can produce a similar electromagnetic environment to that of nearby return strokes at ground level.

V. DISCUSSION AND CONCLUSIONS

In this paper, we have compared calculations of the electromagnetic environment in the frequency range 10^4–10^7 Hz produced near ground by direct and nearby lightning return strokes with those due to the NEMP produced by an exoatmospheric burst. In that frequency range, the calculated Fourier amplitude spectra of the magnetic fields 1 m from a direct lightning strike by an average return stroke are greater than that of the NEMP. The spectra of severe nearby first return strokes at about 50 m exceed that of the NEMP below about 10^6 Hz of average nearby first strokes below about 3×10^5 Hz. These results follow primarily from the time-domain return stroke currents given in Tables IA and IIA, which were determined by theory from measured time-domain electric and magnetic fields. The frequency spectra calculated from fields computed using these currents are in excellent agreement with measured frequency spectra up to 10^7 Hz for lightning at a distance of 50 km, as is evident from Fig. 3, providing confidence in the model currents.

Although many of the computations in this paper were performed for an idealized aircraft near ground, the basic results are applicable to any similar size ground-based system and, to the extent discussed, to aircraft at flight altitudes.

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